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The Physiological Consequences of Acceleration During Shuttle Running

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Abstract
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This study examined the acceleration demands associated with changing direction and the subsequent physiological consequences of acceleration during running at 3 submaximal speeds. 10 male professional footballers completed four 600 m running bouts at 3 speeds (2.50, 3.25 & 4.00 m·s^{-1}). Each bout was in the format of either: i) 3 laps of a 200 m track (CON), ii) ten 60 m shuttles (S60), iii) twenty 30 m shuttles (S30), or iv) thirty 20 m shuttles (S20). Peak heart rate (HR$_{PEAK}$), blood lactate concentration (BLa) and RPE (Borg CR-10) were recorded for each bout. A single change of direction required 1.2, 1.5 and 2.0 s of acceleration at running speeds of 2.50, 3.25 and 4.00 m s^{-1} respectively. An increase in time spent accelerating produced a linear increase in BLa (r=0.43–0.74) and RPE (r=0.81–0.93) at all speeds. Acceleration increases linearly with change of direction frequency during submaximal shuttle running. Increased time spent accelerating elicits proportional increases in perceived exertion, BLa and HR$_{PEAK}$. The current study further underlines the need to consider acceleration when quantifying training load during activities involving numerous changes of direction.

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Introduction
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During intermittent team sports such as football, numerous accelerations and decelerations take place, both with and without changes of direction (CoD) [5, 25]. To date, the majority of studies examining the physiological demands of team sports have focussed on assessing global demands such as the total distance covered within pre-defined locomotion categories during simulated or actual game play [15, 16, 24]. Although such work has increased our understanding of the gross demands of field sports, the failure to consider the effect of CoD, accelerations, and decelerations, may potentially underestimate the physiological demands of the sport.

Hatamoto et al. [18] examined in more detail the cost of changing direction (180° turn) during running at very low speeds of 1.2 and 1.5 m·s^{-1}. The authors employed several different shuttle lengths in order to manipulate CoD frequency (CoD*f*) and allow the energy expenditure of a single CoD to be examined. The study found that the energy cost of shuttle running was significantly correlated to CoD*f*, and was approximately 67% greater per CoD at 1.5 compared to 1.2 m·s^{-1}. The additional physiological demand of CoD appears to be dependent upon the magnitude and duration of acceleration performed [14, 22]. However this is yet to be directly studied in the field as previous research has used only the number of turns as the independent variable.

To date, there have been no studies that have examined the relationship between CoD*f*, the associated acceleration demands, and the physiological response in professional team sports players. Further, with the exception of Hatamoto et al. (2013), previous research in this area has focused on high- and maximal-speed running. Despite evidence that accelerations occur frequently during football, and that a large proportion of the distance covered during football matches is at submaximal speeds [3, 5, 23], there is currently a lack of published data examining the physiological consequences of acceleration at submaximal speeds. Therefore the primary aim of this study is to investigate the effect of acceleration on physiological and mechanical parameters at submaximal running speeds.

Methods

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10 male professional footballers volunteered to participate in the study. Their mean ± SD age, height, body mass and body fat percentage were 19.7±0.4 years, 78.2±6.4 kg, 1.83±0.07 m, and 8.3±2.2%, respectively. All participants had been full time professional football players for at least 3 years and were engaged in regular football training and competition. Participants were given full details of the study procedures and provided written informed consent prior to participating. All experimental procedures received approval from the Institutional Ethics Review Board and meet the ethical standards of the IJSM [17].

All participants completed 2 familiarisation trials occurring 14 and 7 days prior to the first testing period. Participants were asked to adhere to their normal hydration, sleep and nutritional habits in the 48 h prior to all testing. Thereafter on 3 separate occasions and 10 min following a standardised warm-up consisting of 5 min jogging and practitioner-lead dynamic stretching, participants completed four 600 m bouts in a random counterbalanced order. The four 600 m bouts were completed in the following conditions i) 3 laps of 200 m track (CON); ii) ten 60 m shuttle runs (S60); iii) twenty 30 m shuttle runs (S30); iv) thirty 20 m shuttle runs (S20). Each 600 m bout was separated by a 5 min passive rest period. Trials were conducted at the same time of day, 7 days apart, and preceded by 24 h of rest (i.e., no formal football training). All 4 trials on each occasion were completed at one of 3 mean speeds (2.50 m·s^{-1}, 3.25 m·s^{-1} and 4.00 m·s^{-1}). The running speed of 2.5 m·s^{-1} was used as it represented the mean speed recorded during 6v6 small-sided games (unpublished data). The greatest speed of 4.00 m·s^{-1} was selected as it is commonly utilised in time-motion analysis to demarcate the onset of "high intensity running" [15].

All testing was completed on an indoor artificial grass surface. The 200 m track and shuttle runs were measured using a tape measure and a calibrated trundle wheel. Running lanes were 1 m wide and marked using cones at 20 m intervals. In each condition pacing was controlled via a custom audio track played over a loud speaker. Participants were instructed to start on the first audio signal, and that each subsequent audio signal marked the point at which they should have reached the next cone (travelled 20 m). Instructions regarding adhering to lane markings, covering the full distance of each shuttle, and correct pacing were provided on each occasion. All participants were fitted with a heart rate monitor Team 2 system, Polar Electro, Finland and a 10 Hz GPS device with integrated 100 Hz tri-axial accelerometer (MinimaxX S4, firmware 6.75, Catapult Innovations, Melbourne, Australia), with the latter worn in a tight fitting garment to reduce movement artefact. Each participant was assigned their own GPS device and garment which they used throughout the study to eliminate inter-device variability [2].

3 min following the cessation of each bout participants provided a 20 µl capillary blood sample from a fingertip for analysis of blood lactate concentration (BLa). Blood was mixed in 1 mL of hemolyzing solution before being analysed using an automatic blood lactate analyser (Biosen 5030, EKF-diagnostic GmbH, Germany). The validity and reliability of the Biosen 5030 has been previously demonstrated [11]. Participants were asked to provide a rating of perceived exertion (RPE) using Borg's CR10 scale immediately following capillary blood sampling [6].

Heart rate was sampled throughout and recorded at 1 Hz for the determination of peak heart rate (HR$_{PEAK}$) which was taken as the mean heart rate in the final 15 s of each bout. Anteroposterior (FWD), medio-lateral (SIDE) and vertical (UP) inertial forces were sampled and recorded at 100 Hz using the integrated tri-axial accelerometer in the GPS device, the reliability of which has recently been demonstrated [7].

An indoor facility was used in order to control for environmental conditions known to affect the physiologic and kinematic demands of running such as running surface and wind speed [8]. Although the validity and reliability of the 10 Hz GPS used in the current study has been established [2, 26] the validity of these devices for indoor use has not. Therefore, to quantify the acceleration demands of each of the 12 conditions (3 speeds × 4 conditions), participants repeated each protocol outdoors for the purpose of time-motion data collection only on a separate occasion. Following outdoor data collection GPS data were downloaded using the manufacturers supplied software (Sprint 5.0, Catapult Innovations, Australia). Peak speed and time spent > ± 1 m·s^{-2} for each participant from each bout was recorded and retained for analysis.

Data from the 3 testing sessions were downloaded from the GPS devices using the manufacturers supplied software. Heart rate and accelerometer data were then exported to Microsoft Excel. 100 Hz accelerometer data were rectified and summed over the duration of each bout. All data were tested for normality and equality of variance using the Shapiro-Wilk test and Levene's test for equality of variance respectively and found to be normal (P > 0.05). Within-speed, between-condition differences were expressed as mean (95% confidence intervals). A true differences is defined as one in which the 95% confidence intervals of the between-condition difference does not overlap zero. Effect sizes ES were also calculated and defined as trivial (< 0.2), small (0.2–0.5), moderate (0.5–0.8) and large (> 0.8) [10]. To examine the relationship between time spent > ± 1 m·s^{-2} and selected dependent variables, individual regression lines were constructed for each participant, The mean slope and intercept of all participants was then calculated [4]. The operationally defined thresholds used for acceleration were selected based on evidence of an acceleration-dependent validity and reliability of the GPS units used [2]. Repeated measures ANOVA was used to examine within-speed between-condition differences in acceleration and peak speed with an alpha level of 0.05 accepted as significant.

Results

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A single CoD required 1.2, 1.5 and 2.0 s of acceleration at 2.50, 3.25 and 4.00 m s^{-1} respectively. An increase in CoDf resulted in an increase in the percentage time spent accelerating at all speeds (p < 0.01) (○ **Fig. 1**). Moderate to large within-speed, between-condition differences were found for RPE (○ **Fig. 2a**), BLa (○ **Fig. 2b**) and HR$_{PEAK}$ (○ **Fig. 3**).

The confidence interval of the slope for RPE vs. time spent > ± 1 m·s^{-2} was 0.05–0.08 at 2.5 m·s^{-1} (r^2 = 0.78), 0.05–0.08 at 3.25 m·s^{-1} (r^2 = 0.66), and 0.06–0.08 at 4.00 m·s^{-1} (r^2 = 0.86). Large between-condition effects for RPE were found at all speeds indicating that time spent accelerating impacts the perception of exertion at the speeds examined (ES: large).

Analysis revealed the mean slope for BLa was similar between 2.5 m·s^{-1} and 3.25 m·s^{-1} (95% CI: 0.01–0.03 and 0.01–0.05 respectively) but significantly increased at 4.00 m·s^{-1} (95% CI: 0.06–0.10) (○ **Fig. 2b**). At all speeds mean BLa following S20 was greater than all other conditions (ES: large). S30 was greater
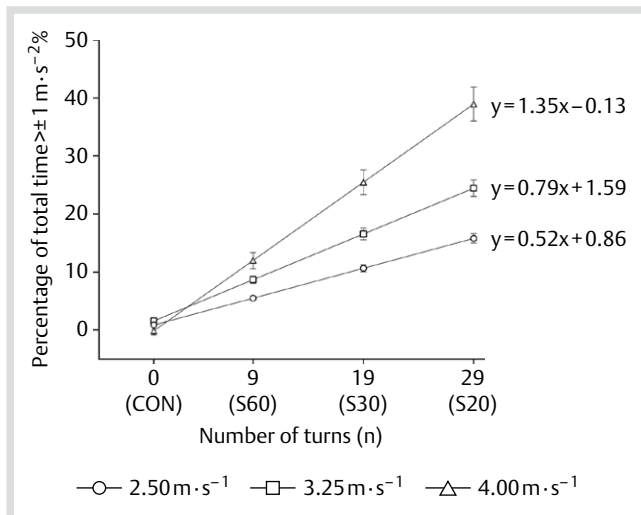
Fig. 1 Least squares linear regression (solid line) ± 95 % CI (error bars) examining time spent accelerating > ±1 m·s^{-2} per change of direction at the speeds examined. Values are percentages of total trial duration. S20, thirty 20 m shuttles; S30, twenty 30 m shuttles, S60, ten 60 m shuttles; CON, 3 laps of a 200 m track.

than S60 (ES: moderate) and CON (ES: moderate to large). Mean BLa following S60 was greater than CON (ES large) at 2.50 m·s^{-1} and 4.00 m·s^{-1}, but did not differ at 3.25 m·s^{-1} (ES 0.0).

In all conditions and at all speeds HR$_{PEAK}$ tended to increase as CoDf increased (○ **Fig. 3a**). At 2.50 m·s^{-1} differences from CON ranged from trivial during S60 to large during S20. At 3.25 m·s^{-1} effects ranged from small during S60 to large during S20. At 4.00 m·s^{-1} effect sizes ranged from trivial during S60 to large during S20. However only at 3.25 and 4.00 m·s^{-1} did analysis reveal significantly non-zero slopes of 0.23 to 1.39 beats ($r^2 = 0.19$) and 0.13 to 0.58 beats ($r^2 = 0.21$) respectively.

No true differences in FWD were found at 2.50 m·s^{-1} with S20 being 2.5 % greater than CON (95 % CI = −0.2, 5.2; ES = trivial) (○ **Fig. 3b**). At 3.25 m·s^{-1} between-condition differences were larger with S20 being 14.9 % greater than CON (95 % CI = 4.6, 25.2; ES = large). At 4.00 m·s^{-1} S20 was 18.1 % greater than CON (95 % CI = 4.1, 32.1; ES = large). However only at 4.00 m·s^{-1} did analysis reveal a significantly non-zero slope indicating that FWD increased linearly (95 % CI = 1.32 to 6.88 arb. units; $r^2 = 0.19$).

Between-condition differences in SIDE existed only at 3.25 m·s^{-1} (○ **Fig. 3c**). S20 was 7.3 % (95 % CI = 2.3, 11.8) greater than CON (ES: moderate). However at 4.00 m·s^{-1}, despite no true differences, S20 tended to be greater than S60 and CON (ES: moderate). There were no true between-condition differences in vertical force (UP) at any speed (ES: trivial).

There were no within-speed between-condition differences in peak speed at any of the 3 speeds tested (p = 0.1). However there was a trend for peak speed during CON and S60 to be greater than S30 and S20 (ES small). Between-participant variation (CV%) in acceleration > ±1 m·s^{-2} ranged from 3 to 12 % at 2.5 m·s^{-1}, 5 to 9 % at 3.25 m·s^{-1}, and 6 to 15 % at 4.00 m·s^{-1}. Intra-individual reliability in time > 1±m·s^{-1} from 4 repeated shuttle protocols (CV%) was 4 %.

Discussion

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The objectives of this study were to i) examine the relationship between change of direction frequency and time spent accelerating during shuttle running, and ii) investigate the relationship between time spent accelerating and the physiological response at 3 submaximal running speeds. Results revealed that as CoDf increased, time spent accelerating increased linearly; with an increase in mean speed producing a greater time spent accelerating per turn (○ **Fig. 1**). Blood lactate concentration increased linearly at a greater rate at 4.00 m·s^{-1} compared to 3.25 and 2.50 m·s^{-1}. Rating of perceived exertion increased linearly at the same rate across all speeds (○ **Fig. 2**).

Within-speed between-condition difference in measures of physiological and kinetic demand proportional to the time spent accelerating are evident from the current analysis. We observed true between-condition differences for BLa, RPE, HR$_{PEAK}$ and inertial forces (FWD and SIDE) at all speeds, highlighting the acceleration dependent mechanical and physiological impact of performing CoD at sub-maximal speeds.

Acceleration elicits a greater metabolic demand as well as a greater neural activation of the working muscles compared to constant speed running [20, 21]. It is proposed that the elevated physiological demand is due in part to the increased time under tension required by the working muscles to generate the forces required to overcome the body's inertia, resulting in increased recruitment of larger motor units and less efficient type II muscle fibres [14]. Additionally, the increased involvement of upper body muscles responsible for postural stability are also thought to contribute to the elevated cardiorespiratory demand seen during change of direction tasks [19].

The findings of the current study concur with previous work reporting a greater physiological demand associated with change of direction tasks [9, 12, 18]. Buglione & di Prampero [9] recently examined the effects of average speed and shuttle distance on the energy cost of shuttle running. Although Buglione & di Prampero [9] did not directly measure acceleration and the protocol differed from the current study, similar trends were observed. For instance, during continuous running at 2.78 m·s^{-1} mean blood lactate concentration in recreationally active participants increased from 1.3 ± 0.8 mmol/L[1] during linear running, to 2.37 ± 1.9 mmol/L[1] when completing the same distance in 20 m shuttles, to 7.3 ± 3.0 mmol/L[1] when completing 10 m shuttles. In general agreement with the study of Hatamoto et al. [18] and the current study, the authors found that indirect measures of the energy cost of shuttle running was dependent on mean speed and CoDf.

Interestingly, in the current study the rate at which RPE increased did not differ between speeds (○ **Fig. 2a**). This finding is in agreement with Hatamoto et al. [18] who reported that the slope of the regression equation between RPE and CoDf was not different at 1.2 and 1.5 m·s^{-1}. In contrast, the rate of increase of blood lactate concentration was greater at 4.00 m·s^{-1} compared to 2.50 and 3.25 m·s^{-1}. Inspection of the intercept of the regression equations suggests this increase may be largely due to mean speed. For instance, the CON trial at the 3.25 and the 4.00 m·s^{-1} speeds did not elicit greatly different time spent accelerating, however the 95 % CI of the intercept of the slopes were 1.02–2.35 and 3.98–5.73 respectively.

The lack of, and trivial-to-small between-condition differences in parameters of mechanical load were not consistent with our hypothesis. Due to increased ground contact time and ground
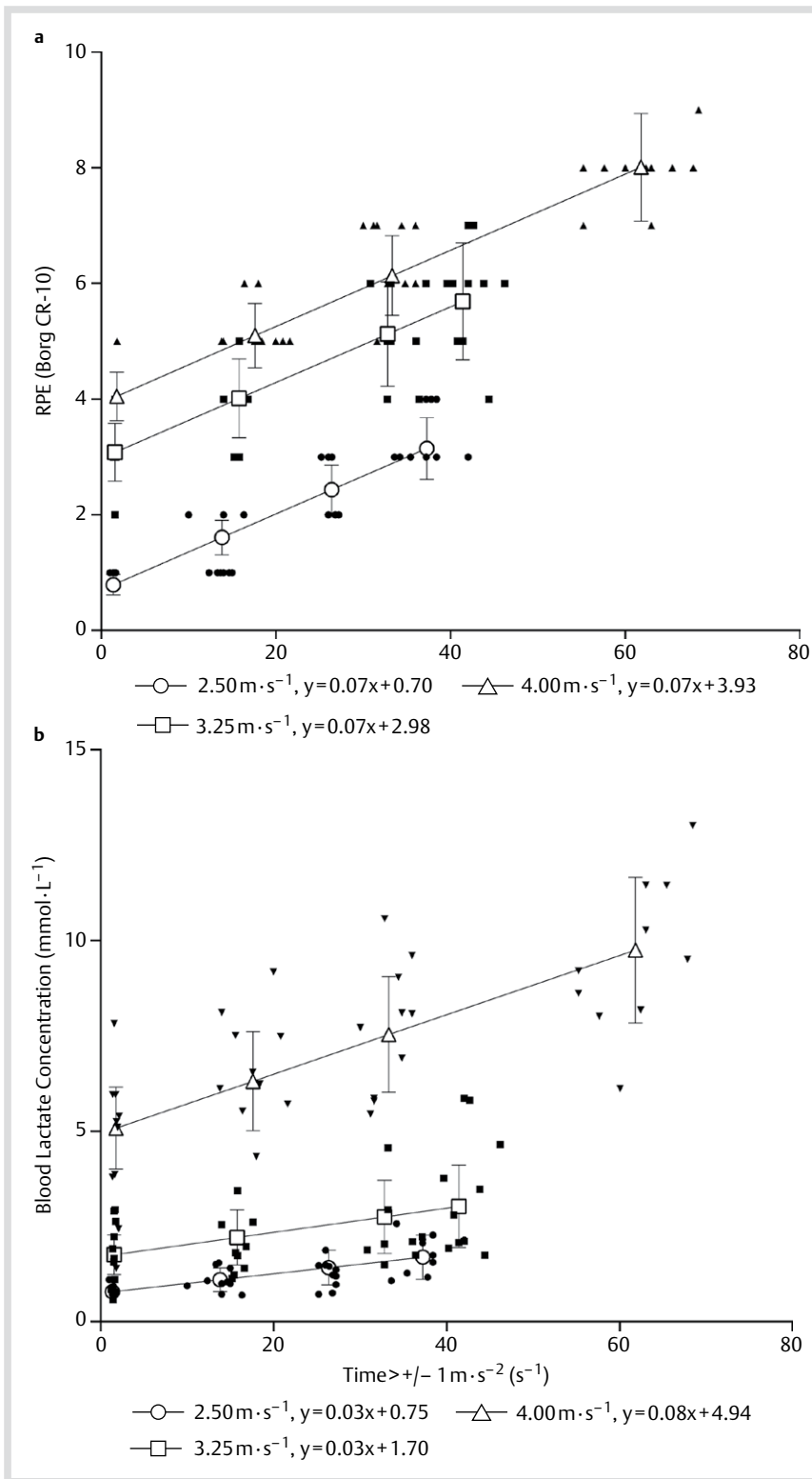
Fig. 2 Mean relationship between time spent accelerating $> \pm 1\,m \cdot s^{-2}$ and RPE **a**, blood lactate concentration **b** at the 3 speeds examined superimposed over individual data points. The slopes of the RPE regression equations did not differ across speeds. The slope of the blood lactate concentration regression equation at $4.00\,m \cdot s^{-1}$ was significantly different from $2.50\,m \cdot s^{-1}$ and $3.25\,m \cdot s^{-1}$.

reaction forces associated with accelerating it was expected that greater differences would be observed between conditions [9,14]. An explanation may lie in the upper thoracic position of the accelerometer. The ground reaction forces encountered during running are likely dissipated through the posterior kinetic chain [1,13], and as a result perturbations of the accelerometer are likely diminished. Additionally, the changes in orientation of the accelerometer due to increased forward lean and trunk flex-

ion during acceleration and deceleration respectively may compromise the accuracy of the accelerometer.

The current analysis did not reveal consistent between-speed differences across all speeds for peak heart rate. Similarly, Dellal et al. [12] reported that heart rate measures (% HR reserve) did not differ significantly between intermittent in-line and shuttle protocols at 100, 105 and 110 % v$\dot{V}O_2$max lasting less than 10 min. The authors proposed that the high forces required to
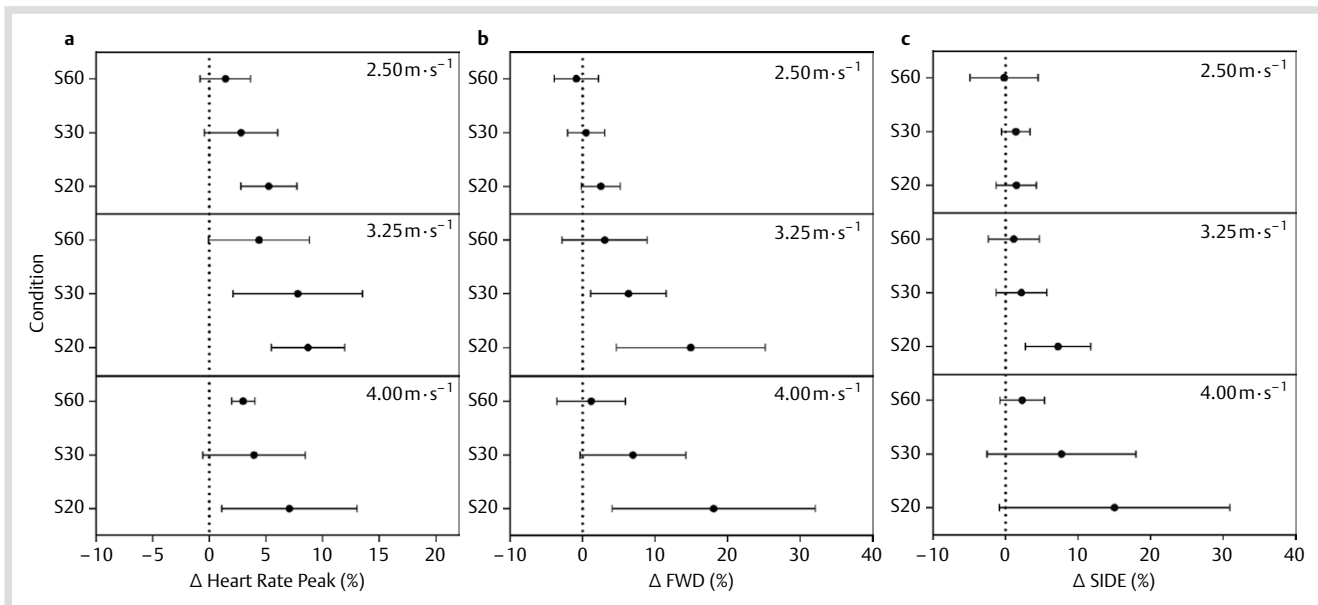
Fig. 3 Mean percentage difference (±95% CI) from CON in HR$_{PEAK}$ **a**, FWD **b** and SIDE **c** for all conditions. S20, thirty 20 m shuttles; S30, twenty 30 m shuttles, S60, ten 60 m shuttles; CON, 3 laps of a 200 m track.

accelerate during CoD likely increases the reliance on Type II fibres, leading to elevated blood lactate concentration and a reduced efficacy of heart rate to reflect the energy cost of the exercise.

We acknowledge that the 180° CoD used in the current study do not replicate the typical CoD activities of team sports [5]. However the purpose of the CoD in the current study was to manipulate acceleration in a controlled format to allow for the examination of the selected dependent variables. Unpublished data from our group shows that during small sided football games time spent accelerating $>\pm 1\, m\cdot s^{-2}$ typically accounts for 20 to 25% of total game time. In the current study the percentage of time spent accelerating during S20 approximated 16, 22 and 40% at 2.50, 3.25 and 4.00 m·s^{-1} respectively, reflecting a range encompassing typical values observed during training in professional players.

As suggested by Hatamoto et al. [18], further research examining the effects of different turning angles and running speeds is required. Moreover, there exists a strong justification for a thorough examination of the physiological response to performing accelerations of differing magnitudes. The current study is the first to directly examine acceleration in this way, but looked only at acceleration $>\pm 1\, m\cdot s^{-2}$ which does not allow for discriminative examination of the magnitude of acceleration. Further, there also exists a physiological rationale to discriminate between positive and negative acceleration. When decelerating (negative acceleration), eccentric muscle actions predominate which are more efficient than concentric actions. Indeed, the energy cost of decelerating may approximate only one third of the energy cost of the equivalent rate of accelerating [23], however the implications of this have not been examined.

Conclusion
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Acceleration increases linearly with CoDf during submaximal shuttle running. Increases in time spent accelerating elicits proportional increases in perceived exertion, BLa and HR$_{PEAK}$. The current study further underlines the need to consider acceleration when quantifying training load during multidirectional activities such as team sports. The implications for how training is quantified within team sports are clear; accelerations, even at submaximal speeds, are physiologically relevant. Commonly used parameters in contemporary time-motion analysis (total distance, high-speed distance) do not consider acceleration and therefore may not adequately reflect the physiological demand of team sports. Additionally, practitioners prescribing exercise involving CoD should be aware that the prescription should not solely be based on the intended mean speed, but also on the frequency and magnitude of the associated acceleration. Further research is needed to elucidate the effect of turning angle, and acceleration magnitude on physiological response.

Acknowledgements
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