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2 Metabolic power requirement of change of direction speed in

3 young soccer players: Not all is what it seems.

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Abstract

Purpose. The aims of this study were to 1) compare the metabolic power demand of straight-line and change of direction (COD) sprints including 45° or 90°-turns, and 2) examine the relation between estimated metabolic demands and muscular activity throughout the 3 phases of COD-sprints.

Methods. Twelve highly-trained soccer players performed one 25-m and three 20-m sprints, either in straight-line or with one 45°- or 90°-COD. Sprints were monitored with 2 synchronized 100-Hz laser guns to assess players' velocities before, during and after the COD. Acceleration and deceleration were derived from changes in speed over time. Metabolic power was estimated based on di Prampero's approach (2005). Electromyography amplitude (RMS) of 2 lower limb muscles was measured. The expected energy expenditure during time-adjusted straight-line sprints (matching COD sprints time) was also calculated.

Results. Locomotor-dependant metabolic demand was *largely* lower with COD (90°, 142.1 ± 13.5 J.kg^{-1}) compared with time-adjusted (effect size, ES = -3.0; 193.2 ± 18.6 J.kg^{-1}) and non-adjusted straight-line sprints (ES = -1.7; 168.4 ± 15.3 J.kg^{-1}). Metabolic power requirement was angle-dependent, *moderately* lower for 90°-COD vs. 45°-COD sprint (ES = -1.0; 149.5 ± 10.4 J.kg^{-1}). Conversely, the RMS was *slightly*- (45°, ES = +0.5; +2.1%, 90% confidence limits (±3.6) for vastus lateralis muscle (VL)) to-*largely* (90°, ES = +1.6; +6.1 (3.3%) for VL) greater for COD-sprints. Metabolic power/RMS ratio was 2 to 4 times lower during deceleration than acceleration phases.

Conclusion. Present results show that COD-sprints are largely less metabolically demanding than linear sprints. This may be related to the very low metabolic demand associated with the deceleration phase during COD-sprints that may not be compensated by the increased requirement of the reacceleration phase. These results also highlight the dissociation between metabolic and muscle activity demands during COD-sprints, which questions the use of metabolic power as a single measure of running load in soccer.

Key words: Energy demand, muscular activity, electromyography amplitude, acceleration, deceleration, sprint, braking forces, running load.

Introduction

In team sports (e.g., soccer, basket-ball, hand-ball), the ability to quickly accelerate/decelerate during sprints with or without a change of direction (COD) is decisive for game-deciding situations (e.g., winning a ball, creating and stopping goal scoring opportunities [1-3]. Professional soccer players can perform on average more than 8 CODs per minute during a match [4] and about 3 fold more high accelerations (> 2.5 m.s^{-2}) than sprints [5]. In addition, the ability to change of direction while running has been recognized as an important factor for a successful participation in team sports [6]. The acceleration-deceleration dynamics associated with repeated CODs require high levels of mechanical (e.g., eccentric contractions) and metabolic load [7], which may be reflected by increases in markers of muscular damage following soccer training [8] and matches [9]. The exact mechanical and metabolic responses to COD speed remain however unclear, and the influence of COD angle and speed has not been clearly established. A better understanding of the energy demands of un-orthodox movement patterns [2] which characterize COD speed may be useful to assess the actual energy requirements of training and match situations.

Empirical and scientific evidences suggest that running with COD increases the energy demands of human locomotion. Compared with straight-line runs, greater blood lactate concentration ([La]$_b$), heart rate (HR) [10,11] and oxygen uptake ($\dot{V}$O$_2$) [10] have been reported during both supramaximal [10,11] and submaximal [12] running exercises. In these studies however, speed or distance was not adjusted for the time lost during the turns, so that the respective effect of COD *per se* could not be properly examined. In a recent study, Hatamoto et al. [13] estimated the energy cost of a single 180°-COD using

1   repeated runs with different turns frequency (i.e., different frequency accumulation

2   method). Results showed that the energy cost increased with running velocity, but only

3   very low intensities were examined (i.e., < 9 km.h^{-1}); the actual cost of COD at higher

4   running speed as during training and matches remains unknown. Another alternative to

5   isolate the metabolic effect of CODs *per se* is to use runs over time-adjusted distances,

6   i.e., adjusted COD running distances matched for straight-line sprint time [14,15].

7   Compared with straight-line runs, COD-adjusted runs elicited equivalent $\dot{V}O_2$ and

8   variable [La]$_b$ responses: [La]$_b$ were lower during repeated sprints with COD [12] but

9   greater during high-intensity intermittent runs [15]. These latter measures were however

10   limited to systemic/whole-body responses. The direct limitation of this approach is that

11   the estimated energy demands can be contaminated by the additional requirements of the

12   upper-body limbs [10], and that exclusively locomotor-related demands can't be isolated.

13   To assess the locomotor-related energy demands in the field, di Prampero et al.

14   [16] introduced a new approach based on the estimated energy cost of accelerated and

15   decelerated running. While this approach has been used in three studies to report the

16   overall locomotor-related metabolic demands during soccer games and during

17   submaximal intermittent shuttle runs [7,17,18], the soccer-specific (i.e., between 0 and

18   90°-COD) demands of COD-sprints is still unknown. Additionally, the respective

19   contribution of the deceleration, turning and re-acceleration phases to the overall COD

20   energy requirement hasn't been examined. Practically, the methods generally used to

21   assess locomotor patterns in the field during training and matches may have limitations

22   when it comes to the investigation of COD speed. For instance, global positioning

23   systems (GPS) or local position measurements are commonly-used but may have limited

1   validity and reliability for such short and intense movement patterns [19-21]. The use of

2   laser guns, which present acceptable reliability and validity to assess changes in velocities

3   [22], may offer an alternative to practitioners willing to assess the different kinematic

4   phases and metabolic requirement of COD speed.

5   In addition to the aforementioned metabolic responses, CODs affect substantially

6   lower limb muscle activity as assessed via electromyography (EMG). Compared with

7   straight-line runs, EMG activity has been reported to increase during runs with COD

8   [23,24]. This increase may be related to the increased external load placed on the knee

9   joint [23] and the need for applying high lateral forces on the ground [25]. However, very

10   little is known about the changes in lower limb muscle activity during the different

11   phases of the CODs (i.e., acceleration, deceleration, turn). Moreover, how these potential

12   changes in EMG activity relate to changes in metabolic requirement during the different

13   phases of COD speed is also unknown. Finally, since performance [6,26], physiological

14   and muscular activity [14,15] responses during COD speed are likely COD angle-

15   dependent, the locomotor-related metabolic demands and their relationship with muscular

16   activity may also be COD-angle dependent. However, this has still to be examined.

17   In an attempt to describe the detailed kinematics and metabolic demands of the

18   different COD phases in the field, we have recently developed a new timing system

19   combining two laser guns, which allows the continuous tracking of the players before,

20   during and after the COD [22]. This system allows the monitoring of different center of

21   mass (COM)-related kinematic variables during COD speed [22], with reasonable levels

22   of reproducibility (small-to-moderate standardized coefficients of variation (CVs) [22].

23   The aims of the present study were therefore to examine 1) the metabolic power demands

of field-based straight-line and COD sprints including either 45° or 90°-turns, while accounting or not for the time lost when changing direction, 2) the relation between estimated metabolic demands and lower limb muscles activity and, 3) an eventual angle-dependence of metabolic and lower limb muscles activity demands during COD-sprints.

Materials and Methods

Participants.

Twelve highly-trained young soccer players (age: 16.5 ± 0.4 yr, age from estimated peak height velocity [27]: 2.1 ± 0.6 years old, height: 170.3 ± 6.4 cm, body mass 60.0 ± 6.3 kg, sum of 7 skinfolds: 45.6 ± 16.0, 10-m sprint time: 1.76 ± 0.05 s and maximal sprinting speed: 29.9 ± 1.2 km.h-1) from an elite academy were involved. Anthropometric and performance data were collected as previously described. All the players participated on average in ~14 hours of combined soccer-specific training and competitive play per week (6-8 soccer training sessions, 1 strength training session, 1-2 conditioning sessions, 1 domestic game per week and 2 international club games every 3 weeks). All players had a minimum of 3 years prior soccer-specific training and were well familiar with the testing procedures. Written informed consent was obtained from the players and their parents. The study was approved by the Anti-Doping Lab Qatar (ADLQ) Ethics Committee and conformed to the recommendations of the Declaration of Helsinki.

Experimental overview.

1   Following a 15-min standardized warm-up, including eight consecutive COD-runs with

2   progressive increased speed for familiarization, players randomly performed two 40-m

3   sprints in straight-line (SL) with 10-m splits, two 20-m sprints with one left 45º-COD,

4   two 20-m sprints with one left 90º-COD after 10 m, and two 25-m sprints with one left

5   90º-COD after 15 m ($90°_{25}$). The angles of 45° and 90° were chosen since the majority of

6   COD-runs in soccer matches occur within a range of 0 to 90° [4]. The use of a single

7   COD during the sprints was chosen to determine the energy demand per COD and also

8   for specificity with regard to soccer practice during matches [28]. As a part of the

9   academy performance screening (i.e., three times per year), players' anthropometric

10   measures and maximum sprinting speed [29] were available and then, included as

11   possible determinants to COD-sprint performance. In addition, all the players were

12   familiarized with this type of COD-sprint while being routinely tested during the

13   academy performance screening on a similar 90°-COD sprint. Players were required to

14   initiate the left turn with a strong impulse of their right foot, positioned in the centre of

15   the running course, at the level of the turn. A posteriori, it appeared that all the players

16   performed naturally the 90°-COD sprints as requested (i.e., strong right foot impulse to

17   initiate the turn). Players' dominant leg (i.e., the kicking leg) was the right one for all. In

18   the present study, all players turned on the left during the COD-sprints. Whether different

19   responses could have been observed with a right turn could not be examined in the

20   present study, which is a limitation. However, Castillo-Rodriguez et al. [30] observed that

21   amateur players kicking with their right foot were very likely to present a greater COD-

22   sprint performance on the left side. All players turned largely faster to the left side than

23   the right side (i.e., effect size = 1.8). There was a 2-3 min passive recovery period

1 between each sprint. To increase ecological validity, players commenced each sprint from

2 a jogging start (2 m.s^{-1}, controlled with a metronome) over 10 m, and were instructed to

3 initiate their sprint when reaching a cone placed 1 m from the starting line (Fig. 1). Tests

4 were performed with soccer boots on an outdoor (temperature 39.5 ± 1.5 ℃ and relative

5 humidity 18 ± 2.6 %) grass soccer pitch.

6 **Fig. 1. Experimental set up with the new timing methodology combining two speed**

7 **guns synchronized**. See methods for details.

8 To account for the time lost while changing direction, the distance for straight-line sprints

9 was individually adjusted [15] using the ratio between the straight-line and COD-sprints

10 as follows:

11

12 Adjusted straight-line distance (m) =

13   COD-sprint time (s) x COD-sprint distance/Straight-sprint time (s) (1)

14

15 Accordingly to the equation (1), we calculated adjusted straight-line distances

16 corresponding to 20-m 45°-COD sprints, 20-m and 25-m 90°-COD sprints.

17

18 ***Estimated metabolic demands using di Prampero's approach.***

19 Di Prampero et al. [16] suggested that, accelerated running on flat terrain, as a first

20 approximation, is biomechanically equivalent to running uphill at constant speed, up an

21 ''equivalent slope'' (ES) dictated by the forward acceleration [16]. Minetti et al. [31]

22 have shown a relationship between the energy cost of constant-speed running and

23 inclination of the terrain over a wide range of up- or down-slopes. Based on this latter

1   study, di Prampero et al. [16] proposed an equation to estimate the instantaneous energy

2   cost of accelerated running as follows:

3

4    $C = (155.4 \cdot ES^5 - 30.4 \cdot ES^4 - 43.3 \cdot ES^3 + 46.3 \cdot ES^2 + 19.5 \cdot ES + 3.6) \cdot EM \cdot KT$ (2)

5

6   in which C is the energy cost of accelerated running on the specific terrain (in $J \cdot kg^{-1} \cdot m^{-1}$)

7   calculated with di Prampero's approach, ES is the equivalent slope: $ES = \tan(90 - arc_{tan}$

8    $g/a_f)$; g = acceleration due to gravity; a_f = forward acceleration; 3.6 is the energy cost of

9   running on flat terrain at constant speed; EM is the equivalent body mass: $EM = (a_f^2/g^2$

10    $+1)^{0.5}$; and KT is a terrain constant (KT = 1.29, [7]) to take into account the fact that

11   running on a football field is approximately 30% more costly than running on compact

12   homogeneous terrain.

13   The metabolic power (P; $W \cdot kg^{-1}$) was then calculated by multiplying C ($J \cdot kg^{-1} \cdot m^{-1}$) with

14   the estimated (i.e., obtained per meter) speed (v; $m \cdot s^{-1}$) as follows:

15        $P = C \cdot v$ (3)

16

17   Finally, the total estimated energy expenditure (EEE; $J \cdot kg^{-1}$) was determined as the sum

18   of instantaneous EEE obtained for each meter of each sprint.

19   ***Center of mass-related kinematic measures.***

20   Sprints were simultaneously monitored with timing gates (Brower Timing System,

21   Draper, UT, USA, 1 ms resolution) and two cabled-synchronized 100-Hz laser guns

22   (Laveg LDM100, Jenoptik, Germany, Fig. 1). A custom-developed spreadsheet gathered

23   both data files and calculated the whole player's running profile before, during and after

1   the COD [22]. Individual laser measurements show very good validity (average velocity

2   error of ~2% and reproducibility (coefficient of variation, CV: 1-3%) [32] when assessing

3   linear speed [33]. For the purpose of the present study, the reliability of metabolic power

4   during COD speed was also assessed (Table 1). The lower ICC for the 45º trial may be

5   related to the fact that compared with the straight-line or 90º-COD sprints, players could

6   adopt slightly different running patterns when passing the cones. While the players had

7   learnt in the academy to clearly position their right foot to initiate the left turn with a

8   strong impulse on the ground during the 90º-COD sprint, turning at 45º at high speed

9   could be achieved using either the right or the left foot. This may be associated with

10   greater variations in the actual running path and/or body position, which may have

11   increased the possible time differences between the trials [22].

12   **Table 1. Reliability of some metabolic power variables collected with the new timing**

13   **methodology and timing gates during sprints with and without change of direction.**

		Difference (%)	CV (%)	ICC
Mean metabolic power	Straight-line	-0.2 (-4.7;4.5)	4.0 (2.7;8.6)#	0.95 (0.76;0.99)***
(W.kg^{-1})	45°	0.2 (-1.0;1.1)	6.4 (4.5;11.2)##	0.47 (0.02;0.79)
	90°	-0.1 (-6.2;6.4)	8.0 (5.8;13.4)##	0.80 (0.44;0.93)**
Peak metabolic power	Straight-line	-1.2 (-8.6;7.4)	12.5 (8.9;21.3)##	0.61 (0.16;0.90)*
(W.kg^{-1})	45°	1.1 (-6.8;9.6)	10.4 (7.5;17.7)##	0.36 (-0.20;0.74)
	90°	0.7 (-3.5;5.1)	5.4 (3.9;9.0)#	0.70 (0.28;0.90)*

14

Between-trial difference (90% confidence limits), typical error expressed as a coefficient

of variation (CV, 90% confidence limits) and intraclass correlation coefficient (ICC, 90%

confidence limits). The number of '#' symbols stands for small, moderate, large and very

large standardized difference and CV, respectively. For ICC values, the number of '*'

symbols refers to moderate, large and very large magnitudes, respectively.

Electromyography measurement.

Electromyography (EMG) data were collected from the dominant leg (i.e., the leg used to

both kick and turn for the COD), using a sixteen channel Trigno Wireless EMG system

(Delsys INC, Boston, USA). The contracted muscle belly of the vastus lateralis (VL) and

biceps femoris (BF) were identified. Before placing the electrodes in accordance with the

Surface EMG for Non-invasive Assessment of Muscles recommendations (SENIAM)

[34]. The overlying skin was carefully prepared. The hair was shaved, and the skin was

lightly abraded to remove the outer layer of epidermal cells and thoroughly cleansed with

alcohol to reduce the skin–electrode interface impedance. Trigno wireless EMG sensors

(4 silver bars contact) were carefully taped to the belly of each muscle, parallel to the

muscle fibbers, using hypoallergenic adhesive tape and cotton wool swabs to minimize

sweat induced interference. Signals were sampled at 1000 Hz, amplified (1000×) and

band-pass filtered (20–450 Hz). Data were imported from the Trigno base station and

saved for offline analysis with Spike 2 version 5 (Cambridge Electronics Design,

Cambridge, UK). The data were smoothed using route mean squared analysis (RMS),

which was calculated for a 50-ms window. EMG data (µV) were calculated for each step

(active contraction). Onset and offset of muscle activity were determined as a deviation

1   greater than two standard deviations from the mean of three 50-ms windows of inactivity.

2   The fastest 20-m straight-line sprint was also analysed by isolating peak amplitude

3   contractions from the middle of the sprint. The resultant mean amplitudes were averaged

4   and used for normalization, i.e., the EMG data from COD sprints were expressed as a

5   percentage of the EMG measured during the fastest straight-line sprint [35]. Branch et al.

6   [36] have shown that normalizing EMG to a functional task reduced inter-subject

7   variability compared with normalizing to a maximum voluntary contraction. This

8   approach has been used in several studies [23,35,37,38] to normalize EMG signals during

9   dynamic COD tasks.

10   *Data treatment.*

11   Raw (position) data from the first laser gun was zeroed at the starting line, while the

12   second one was zeroed at the COD point. Velocity data was obtained by derivation and

13   then processed using a 4th order low-pass Butterworth digital filter with a cut-off

14   frequency of 0.6 Hz (selected after several trials judged by visual inspection). Then, both

15   speed curves were merged into a unique curve using the first laser readings at the

16   beginning, the second one at the end; the merged interval (COD) was estimated by

17   interpolation of both readings. Finally, data were resampled to provide an estimate of

18   speed at each meter throughout the entire runs. Acceleration and deceleration were

19   derived from meter-to-meter changes in speed over time. Metabolic power and estimated

20   energy expenditure were estimated based on di Prampero's approach [16]. Meter-to-

21   meter RMS data were estimated by interpolation between each burst of muscle activity.

22   *Statistical Analysis*

1 Data in text, tables and figures are presented as mean with standard deviations and 90%

2 confidence intervals/limits (CI/CL). All data were first log-transformed to reduce bias

3 arising from non-uniformity error. The typical error of measurement, expressed as a

4 coefficient of variation (CV, in % and standardized units) and the intraclass coefficient

5 correlation (ICC) were used as measures of reliability [39].

6 Between-sprints standardized differences in the different running variables were also

7 calculated, using pooled standard deviations. Uncertainty in the differences was

8 expressed as 90% CL and as probabilities that the true effect was substantially greater or

9 smaller than the smaller practical difference (between-subjects SD/5). These probabilities

10 were used to make a qualitative probabilistic mechanistic inference about the true effect.

11 The scale was as follows: 25−75%, possible; 75−95%, likely; 95−99%, very likely;

12 >99%, almost certain. Threshold values for standardized differences were >0.2 (small),

13 >0.6 (moderate), >1.2 (large) and very large (>2). The magnitude of the ICC was

14 assessed using the following thresholds: >0.99, extremely high; 0.99-0.90, very high;

15 0.90-0.75, high; 0.75-0.50, moderate; 0.50-0.20, low; <0.20, very low [39]. Finally, the

16 following criteria were adopted to interpret the magnitude of the correlation: ≤0.1, trivial;

17 >0.1-0.3, small; >0.3-0.5, moderate; >0.5-0.7, large; >0.7-0.9, very large; and >0.9-1.0,

18 almost perfect [39]. If the 90% CI overlapped small positive and negative values, the

19 magnitude was deemed unclear; otherwise that magnitude was deemed to be the observed

20 magnitude [39].

Results

The level of reliability of metabolic power related variables was ranged from small to moderate CVs (Table 1).

The COD-time adjusted straight-line distances corresponding to 45°-, 90°- and $90°_{25}$-COD sprints are shown in Table 2.

The EEE during the 20-m straight-line, 45°, 90° and $90°_{25}$-sprints is shown in Fig. 2 and EEE of time-adjusted straight-line sprints were calculated (i.e., 178.9 ± 15.5 J.kg^{-1}, 193.2 ± 18.6 J.kg^{-1} and 217.8 ± 15.5 J.kg^{-1} during straight-line adjusted for 45°- and 90°- and $90°_{25}$-sprint times respectively). The EEE of the 25-m straight-line sprints was also determined (i.e., 193.5 ± 15.3 J.kg^{-1}). The EEE of COD-sprints were almost certainly lower compared with straight-line and even most likely lower compared with adjusted straight-line trials (Fig. 2). EEE was also angle-dependent, almost certainly lower with 90°-COD than 45°-COD (Fig. 2). For all COD-sprints, the estimated energy expenditure was almost certainly lower during the deceleration phases compared with the acceleration phases (Fig. 2).

The relationship between metabolic power and acceleration/deceleration could be represented by a cubic function with a minimum value of metabolic power (i.e., 8.03 ± 2.85 W.kg^{-1}) associated with a deceleration of -2.26 ± 0.18 m.s^{-2} (Fig. 3) and an energy cost of 2.60 ± 0.22 J.kg^{-1}.m^{-1}. Elevated decelerations (i.e., < -2 m.s^{-2}, [7]) were observed at the 8th (-2.34 ± 0.85 m.s^{-2}), 9th (-2.39 ± 0.82 m.s^{-2}) and 10th (-2.12 ± 0.71 m.s^{-2}) meter of 90°-COD sprints and at the 12th (-2.14 ± 0.93 m.s^{-2}), 13th (-2.39 ± 1.05 m.s^{-2}), 14th (-2.55 ± 1.26 m.s^{-2}) and 15th (-2.32 ± 1.40 m.s^{-2}) meter of $90°_{25}$-COD sprints.

1 **Fig. 2. Estimated energy expenditure of sprints with (45° or 90°) or without (i.e.,**

2 **straight-line, SL) one change of direction (COD)**; $90°_{25}$: 25-m sprint with one 90°-

3 COD. The upper panel represents the standardized difference (Std Diff) between COD-

4 and SL sprints. Since $90°_{25}$ vs. 20-m SL sprints could not be properly compared (i.e.,

5 differences in both running time and distance), their standardized difference (black circle)

6 was not provided. The number of '*' and '†' refers to possible, likely, very likely and

7 almost certain between-sprints differences versus the 45°-COD sprint trial, and within-

8 sprint differences vs. the acceleration phases, respectively. The associated number refers

9 to the magnitude of the difference, with 1 standing for small, 2 for moderate, 3 for large

10 and 4 for very large magnitude.

11 **Table 2. Non-adjusted and change of direction-time-adjusted straight-line distances**

	Distances (m)	Sprint time (s)	COD-time adjusted SL-distance (m)
SL	20	2.89 ± 0.13	
45°	20	3.30 ± 0.16 ****4	22.1 ± 1.1‡‡‡4
90°	20	3.70 ± 0.16 ****4††††4	25.1 ± 1.3 ‡‡‡4
$90°_{25}$	25	4.24 ± 0.18 ****4††††4	30.4 ± 1.6 ‡‡‡4

12 COD: change of direction; SL: straight-line; COD-time adjusted straight-line distance:

13 adjusted (i.e., extended) straight-line running distances matched for COD-sprint time.

14 The number of '*' and '†' refers to possible, likely, very likely and almost certain

15 difference versus straight-line and 45°-COD sprint times, respectively. The number of ‡

16 refers to possible, likely, very likely and almost certain difference versus non-adjusted

1   distances. The associated number refers to the magnitude of the difference, with 1

2   standing for small, 2 for moderate, 3 for large and 4 for very large magnitude.

3   **Fig. 3. Relationship between acceleration and metabolic power**

4   In average, VL and BF RMS for all COD sprints were possibly (i.e., 45°) and

5   likely-to-almost certainly (i.e., 90° and $90°_{25}$) greater compared with straight-line (Fig. 4).

6   The EMG amplitude of both muscles were possibly (i.e., BF) -to-very likely (i.e., VL)

7   greater during 90° than 45°-COD (Fig. 4). The speed and RMS (VL and BF) profiles (i.e.,

8   per meter) during the straight-line, 45°, 90° and $90°_{25}$ sprints are shown in Figure 5.

9   Compared with straight-line, EMG activity was possibly-to-likely greater during 45°-

10   COD and almost certainly greater 90°-COD sprints between 8-m and 15-m (Fig. 5).

11   The EMG amplitude during acceleration/deceleration phases was also angle-dependent;

12   while VL and BF RMS were almost certainly greater during acceleration than

13   deceleration with 90°-COD, they were almost certainly lower during 45°-COD sprints

14   (Fig. 5).

15   The overall metabolic power/RMS ratios of COD-sprints were almost certainly lower

16   compared with straight-line (Fig. 6). This ratio was angle-dependent, i.e., very likely

17   lower with 90º-COD than with 45º-COD (Fig. 6). Additionally, all deceleration phases

18   were associated with an almost certainly lower ratio than acceleration phases and there

19   was a very likely greater ratio during 45° than 90°-deceleration phases (Fig. 7).

20   **Fig. 4. Electromyography amplitude (RMS) of 2 muscles during sprints with (45° or**

21   **90°) or without (i.e., straight-line, SL) one change of direction (COD).** The upper

22   panel concerns the vastus lateralis muscle and the lower panel, the biceps femoris muscle.

1   90°$_{25}$: 25-m sprint with one 90°-COD. The number of '*' and '†' refers to possible,

2   likely, very likely and almost certain difference versus straight-line and 45°-COD sprints,

3   respectively. The associated number refers to the magnitude of the difference, with 1

4   standing for small, 2 for moderate, 3 for large and 4 for very large magnitude.

5   **Fig. 5. Electromyography amplitude (RMS) of vastus lateralis and biceps femoris**

6   **muscles and speed profiles during sprints with (45° or 90°) or without (i.e., straight-**

7   **line, SL) one change of direction (COD)**. 90°$_{25}$: 25-m sprint with one 90°-COD. The

8   medial panel represents the standardized difference (Std Diff) of RMS between COD-

9   and SL sprints. The number of '*' and '†' refers to possible, likely, very likely and almost

10 certain difference versus straight-line and 45°-COD sprints, respectively.

11 **Fig. 6. Metabolic power/electromyography amplitude (RMS) ratio of sprints with**

12 **(45° or 90°) or without (i.e., straight-line (SL)) one change of direction (COD)**. 90°$_{25}$:

13 25-m sprint with one 90°-COD; BF: biceps femoris; VL: vastus lateralis. The number of

14 '*' and '†' refers to possible, likely, very likely and almost certain difference versus

15 straight-line and 45°-COD sprints, respectively. The associated numbers represent the

16 magnitude of the standardized difference, with 1 standing for small, 2 for moderate, 3 for

17 large and 4 for very large magnitude.

18 **Fig. 7. Metabolic power/electromyography amplitude (RMS) ratio during the**

19 **different phases of sprints with (45° or 90°) or without (i.e., straight-line (SL)) one**

20 **change of direction (COD)**. 90°$_{25}$: 25-m sprint with one 90°-COD; BF: biceps femoris;

21 VL: vastus lateralis. The number of '*' and '†' refers to possible, likely, very likely and

22 almost certain difference versus straight-line and 45°-COD sprints, respectively. The

1 associated numbers represent the magnitude of the standardized difference, with 1

2 standing for small, 2 for moderate, 3 for large and 4 for very large magnitude.

Discussion

4 The aims of the present study were to examine both metabolic demands and lower limb

5 muscles activity responses to field-based COD-sprints in highly-trained young soccer

6 players. Our main findings are as follow: 1) metabolic demands were almost certainly

7 lower during sprints with COD when compared with straight-line sprints, and this

8 difference was even greater when accounting for the time lost when changing direction,

9 2) in average, VL and BF activity was slightly to almost certainly (i.e., up to ~29%)

10 greater during sprints with COD than without, 3) the metabolic power/RMS ratio was

11 almost certainly lower during deceleration than acceleration phase and, 4) metabolic and

12 lower limb muscles activity demands were angle-dependent.

Metabolic demands of COD speed

14 Despite the large body of research on COD speed [6], the energy expenditure of field

15 sprinting with COD has never been reported. Similarly, the energy demands of COD- and

16 straight-line sprints have never been compared. In the present study, we observed for the

17 first time an almost certainly lower estimated energy expenditure during sprints with

18 COD compared with straight-line (Fig. 2). These results contrast with previous studies

19 where changing of direction during submaximal [12,13] and repeated sprints [10] were

20 associated with a greater physiological load, as evidenced by increased cardiorespiratory,

21 blood lactate and rate of perceived exertion (RPE) responses. However, while we focused

22 in the present study on a locomotor-related indirect approach to estimate energy demands

1   of COD-sprints, this latter was assessed in the previous studies with a direct method (e.g.,

2   systemic physiological measures such as $\dot{V}O_2$ and blood lactate accumulation)

3   [10,12,13]. In contrast to the indirect locomotor-related approach, the direct method may

4   take in account the greater energy demands of non-locomotor muscles involved during

5   COD (e.g., upper-body and back muscles [10]) and the increased internal work related to

6   the likely greater stride frequency during COD-sprints compared with uphill running

7   [40]. While the difference in these approaches could partially explain these contrasting

8   results, a possible underestimation of the actual metabolic cost with respect to the

9   requirement of turning *per se*, not accounted for here, cannot be discounted [17]. An

10   underestimation of the indirect locomotor-related approach has been also reported in

11   three studies with differences ranging from ~15% (between 2 and 2.6 m.s^{-1}, [18]) to

12   ~30% (running at 4 m.s^{-1}, [17] and during a soccer-specific circuit [41]). While two of the

13   latter studies [17,18] focused exclusively on 180°-CODs, the difference in the present

14   study was ~25% with 90°-angle and ~15% with 45°-angle. The underestimation of

15   energy demand using this approach may be related to the fact that di Prampero's equation

16   was established in experienced (endurance) mountain runners [31], who likely present

17   different running economy than soccer players used in other studies [17,18]. In fact,

18   during uphill and downhill running (set equal to accelerated and decelerated running at an

19   equivalent slope), the differences in energy cost may increase between experienced

20   mountain runners and soccer players [17].

21   The lower locomotor-related energy expenditure during entire COD-sprints,

22   compared with straight-line, may also be related to the very low locomotor-related

23   metabolic demands of the deceleration phase during COD-sprints, that may not be

1 compensated by the increased requirement of the reacceleration phase (Fig. 2). In fact,

2 the deceleration phase is characterized by both an important decrease in speed (Fig. 5)

3 and an increase in eccentric muscle contractions, which have been estimated as two to six

4 times less metabolically demanding for the same amount of work than concentric

5 contractions [42,43]. Accordingly, in agreement with Osgnach et al. [7] who suggested

6 that the metabolic demands were lower (i.e., 2.4 $J.kg^{-1}.m^{-1}$) at -2 $m.s^{-2}$, the lowest

7 metabolic demand (i.e., 2.6 $J.kg^{-1}.m^{-1}$) in the present study was observed when

8 decelerating at 2.26 $m.s^{-2}$ (Fig. 3). Finally, the lower energy requirement of COD-sprint

9 compared with straight-line speed was even more apparent when considering the sprints

10 adjusted for the time lost when changing of direction (Fig. 2), reinforcing the findings

11 that COD *per se* may not be as metabolically demanding as we thought.

12 Besides the finding that COD-sprints were less metabolically demanding than in straight-

13 line, we also found that the locomotor-related energy demands of COD-sprints were

14 angle-dependent. Indeed, the almost certainly lower estimated energy expenditure

15 observed during the 90°-COD compared with the 45°-COD sprints could be related to the

16 almost certainly lower acceleration and greater deceleration distances (Table 3). These

17 differences in acceleration and deceleration distances were associated with a likely

18 greater peak deceleration and likely lower peak speed, peak acceleration and speed during

19 the 90°-turn [22]. In previous studies, it was shown that the mean braking forces during

20 the COD phase were largely greater with a 90°- than a 45°-turn at maximal running

21 speed [25,44]. It was concluded that greater direction change angles coincide with an

22 increase of the mean braking forces observed during the COD phase. While a component

23 of the initial momentum developed before the 45°-turn could be transferred to the

1 subsequent outgoing run, the incoming momentum had to be terminated before the 90°-

2 turn, which requires greater braking force [25,44]. Additionally, compared with 45°-

3 COD, largely greater re-acceleration and propelling forces associated with the 90°-COD

4 are actually applied in the frontal plane during the impact phase [25,45]. However, the

5 forward acceleration is the only acceleration component used to determine the locomotor-

6 related energy demands without taking in account the two other components [16].

7 Therefore, the decreased locomotor-related energy demands associated with the greater

8 deceleration phase during the 90°-COD sprints likely explains the lower energy demands,

9 despite the need to regenerate a new momentum for the outgoing run [25].

10 Data from the $90°_{25}$ COD-sprints shows that despite a greater speed reached before the

11 $90°_{25}$-COD, the peak of re-acceleration after COD was similar (Table 3). This indicates

12 that the locomotor-related energy demands of pre-planned 90°-COD sprints may not be

13 affected by greater acceleration and speed before COD (i.e., distance of 15 m vs. 10 m

14 before the COD).

15 Finally, if we consider that the lower locomotor-related energy demands of COD sprints

16 compared with straight-line sprints is related to very low energy demands of the

17 deceleration phase, it can be hypothesized that sprints with greater COD angles would be

18 associated with even lower locomotor-related energy demands.

19 **Table 3. Running variables during sprints with and without changes of direction.**

	Straight-line	45°	90°	90° 25
Peak speed before COD (m.s^{-1})	8.06 ± 0.46	6.65 ± 0.32 ****4	6.40 ± 0.30 ****4††2	7.11 ± 0.41 ****4††††2##4

Peak re-acceleration (m.s⁻²)		0.98 ± 0.40	1.52 ± 0.36 ***3	2.70 ± 0.57 ****4††††3	2.66 ± 0.91 ****4††††3
Peak deceleration (m.s⁻²)			-1.12 ± 0.82	-3.00 ± 0.78 ††††4	-3.29 ± 0.82 ††††4
Acceleration distance (m.s⁻²)	20m		7.71 ± 1.74	4.41 ± 0.62 ††††4	7.55 ± 1.3 ⧺⧺4
Deceleration distance (m)			4.3 ± 1.9	7.1 ± 1.2 ††††4	8.7 ± 0.9 ††††4⧺⧺2

1

2   COD: change of direction; SL: straight-line. The number of '*', '†' and '⧺' refers to

3   possible, likely, very likely and almost certain difference versus straight-line, 45° and

4   90° conditions, respectively. The associated number refers to the magnitude of the

5   difference, with 1 standing for small, 2 for moderate, 3 for large and 4 for very large

6   magnitude.

7

8   ***Lower limb muscles activity demands of COD speed***

9   Compared with straight-line sprints, the overall lower limb muscles (i.e., VL and BF)

10   activity was very likely-to-almost certainly greater (i.e., VL and BF) during 90°-COD

11   sprints, and slightly greater (i.e., VL) during 45°-COD sprints (Fig. 4). To our

12   knowledge, this is the first time that lower limb muscles activity is reported during an

13   entire sprint with COD in the field. When examining 30°- and 60°-COD submaximal

14   runs, Besier et al. [23] reported a substantial increase of VL and BF activity during the

15   impact stance phase during (i.e., ~10 km.h⁻¹), compared with straight-line. Hanson et al.

1   [46] have shown a large increase of both VL and BF activity during the turn of a 45°-

2   COD run. In other studies comparing 45°-COD sprints with straight line runs, muscles

3   activity was averaged over different muscle groups (i.e., quadriceps and hamstring) and

4   EMG activity was reported to be equivalent and lower for quadriceps and hamstring,

5   respectively. These contradictory results may be explained by the heterogeneity of

6   protocols and differences in study designs (e.g., EMG normalization procedure, running

7   speed, angle of the COD, choice of lower limb muscles measured). When monitoring for

8   the first time the muscle activity time course during each run, we found EMG activity to

9   be phase-dependent. Compared with straight-line sprints, the magnitude of the VL and

10   BF activity during specific portions of COD-sprints may explain the greater average VL

11   and BF activity during the whole COD-sprints, compared with straight-line (Fig. 5).

12   COD-sprints elicited substantially greater VL and BF activities especially during and just

13   after the turn (i.e., between the 8th and the 15th meter) (Fig. 5). This latter portion of the

14   sprints is generally associated with the highest deceleration (i.e., 8th to 10th meter) and the

15   highest re-acceleration (i.e., 12th to 15th meter, Fig. 5) patterns, which characterize COD-

16   sprints with large braking and propelling forces to change of direction [25]. Present

17   findings show that the re-acceleration effort at the end of the COD phase elicited largely

18   (45°-COD)-to-very largely (90°-COD) greater peak accelerations compared with the

19   second 10-m part of the straight-line sprints (Table 3). It follows from Newton's second

20   law that greater propulsive force would be required after the turn and would explain the

21   slightly-to-moderately (i.e., 45°-COD) and very largely (i.e., 90°-COD) greater VL and

22   BF activities observed compared with straight-line sprints (Fig. 5). In a previous study

23   during high-intensity running, quadriceps activation increased during the impact phase of

1   a 45°-COD and has been related to greater forces associated with COD compared with

2   straight-line runs [47]. Quadriceps muscles are actually considered as the primary

3   muscles to contribute to the absorption of strong eccentric forces that occur during

4   deceleration ground contacts [38,45]. Throughout concentric contractions, the quadriceps

5   also help to accelerate the body in the propulsive phase of COD-runs [38]. The magnitude

6   of the integrated hamstring activation patterns during the COD impact phase suggested

7   that hamstring muscle group assists the knee in absorbing the forces associated with

8   direction change [47]. In addition, the primary role of the hamstring muscles group

9   during the COD impact phase has been identified as the mechanism by which the motion

10   of the centre of gravity can be decelerated through the stabilisation of the knee [23,37].

11   Besides the co-contraction of flexor and extensor muscle groups, a selected greater

12   activation of BF has been also pointed out during COD to cope with internal rotation

13   moments applied to the knee [23]. Hamstrings are also the prime movers of hip extension

14   which is considered as a fundamental element of (horizontal) propulsion [48]. A transfer

15   from a flexed to an extended hip angle during COD stance has been observed to coincide

16   with high muscle activation of the hamstring group during COD tasks [47]. Therefore, the

17   mechanical demands to change of direction while sprinting and the functional roles of VL

18   and BF might have induced the largely greater VL and BF activities observed during the

19   highest deceleration (8 to 11-m) and re-acceleration (11 to 15-m, Fig. 5) phases of COD-

20   sprints, compared with straight-line. During the other portions of the sprints (i.e., start to

21   7th meter and 16th to 20th meter), the between-conditions difference was unclear or too

22   small to compensate for the substantially greater VL and BF activity during the medial

23   portion of COD-sprints (Fig. 5). In addition, a recent study highlighted the magnitude of

horizontal braking force during the penultimate step prior to the turn, probably as a

deceleration strategy to reduce the resultant ground reaction force during last footfall and,

in turn, influence knee joint loads [49].

When comparing the EMG responses to the different sprint angles over the entire

runs, 90°-COD sprints elicited a possibly (i.e., BF) to very likely (i.e., VL) greater

muscles activity compared with 45°-COD sprints (Fig. 3). Therefore, the magnitude of

difference in VL and BF activity between COD and straight-line sprints may be angle-

dependent. Compared with straight-line sprints, the magnitude of the greater VL and BF

activity observed during the medial portion of 45°-COD sprints was lower (i.e., small to

moderate) than during the same portion of 90°-COD sprints (i.e., large to very large) (Fig.

5). This difference may be associated with a largely-to-very largely greater decelerating

(i.e., greater than 40%) and propelling (i.e., greater than 56%) forces required [25] to

control the incoming and outgoing momentums during the 90°-COD run, respectively

[25]. Accelerations tend to be greater when the movement is initiated from a standing

start; in contrast, accelerations tend to be minimized when initiated once in motion. As

discussed above, the lack of a need to completely regenerate a new momentum with the

45°-condition likely explains the lower reacceleration and the associated lower EMG

activity compared with 90°-conditions (Table 3). It follows from Newton's second law

that both the requirement for braking and propulsive forces increase with the COD angle

[25].

Data from the $90°_{25}$ shows however that further than the angle, the actual speed

reached before the COD may have only a limited effect on lower muscles activity.

Actually, there was no substantial difference of BF and VL activity between 90° and

1   $90°_{25}$ sprints (Fig. 4). This could be explained by the similar muscles activity profile

2   observed between conditions with an equivalent great amount of BF and VL activity

3   during the same portion of COD sprint (i.e., just before, during and just after the turn)

4   (Fig. 5). In addition, BF and VL activities were similar during the deceleration phase (i.e.,

5   35% and 36% of total BF and VL activities, respectively) of $90°$- and $90°_{25}$-sprints (Fig.

6   4). Accordingly, there was no substantial difference in peak deceleration and peak re-

7   acceleration between $90°$ and $90°_{25}$ sprints (Table 3). This may indicate that despite

8   largely greater peak speed and peak acceleration before the $90°_{25}$-COD, an equivalent

9   pattern of VL and BF activity during deceleration and re-acceleration phases was

10 permitted thanks to a substantially longer decelerating distance during $90°_{25}$ sprints

11 (Table 3).

12   In overall, present results show that a 20-m sprint with one COD may elicit a

13 substantially greater activity demand of VL and BF than a 20-m sprint in straight-line.

14 This difference may be explained by the mechanical demands associated with the highest

15 deceleration and re-acceleration patterns. Additionally, VL and BF activity during COD-

16 sprints would increase with the COD angle in relation with a greater requirement for

17 braking and propulsive forces. Finally, the actual speed reached before the COD (during

18 15-m vs. 10-m) may have only a limited effect on BF and VL activity.

19

20 ***Metabolic power/lower limb muscles activity ratio***

21 There were substantial differences in the metabolic power/RMS ratio between straight-

22 line and COD-sprints. Despite the large body of research on COD speed, the direct

23 relation between metabolic power and muscular activity during field sprinting with COD

1   has never been reported. The fact that COD-sprints were characterized by substantially

2   lower metabolic power and greater RMS led to an almost certainly lower ratio compared

3   with straight-line sprints (Fig. 6). This difference highlights the dissociation between

4   metabolic and lower limb muscular activity demands during sprints with COD, and more

5   particularly during the deceleration phase. The metabolic power/RMS ratios of

6   deceleration phase were 2 to 4 times (i.e., very largely) lower than that of acceleration

7   phases (Fig. 6). While the deceleration phase may be categorized by a greater lower limb

8   muscles activity (Fig. 4), the locomotor-related estimated energy expenditure is actually

9   substantially decreased (Fig. 2). It is worth noting that this dissociation between

10   metabolic and muscular activity demands was specific to deceleration phase only, and

11   was not observed during acceleration phases (Fig. 7). In addition, this dissociation seems

12   to be angle-dependent. Compared with the 45°-COD sprint, the metabolic power/RMS

13   ratio was largely lower for 90°-COD sprints. This result is consistent with the

14   substantially greater muscular activity and lower locomotor-related estimated energy

15   expenditure found during 90°-COD sprints. The greater the COD angle, the longer the

16   deceleration phase (Fig. 5) and in turn, the lower the metabolic power (Fig. 2). In

17   addition, the greater the COD angle, the greater the braking and propelling forces [25]

18   and the greater the lower limb muscular activity [23]. These assumptions seem to be

19   confirmed by the largely lower 90°-COD metabolic power/RMS ratio compared with the

20   45°-COD sprints (Fig. 6). Finally, the reported dissociation between metabolic demands

21   and muscle activity is an additional limitation to the use of metabolic power as a single

22   measure of running load in soccer [41].

Conclusions

In the present study, we found that the locomotor-related metabolic demands of sprints with one COD were substantially lower than during straight-line sprints, and that this difference was even most likely greater when accounting for the time lost when changing direction. This may be related to the very low metabolic demands of the deceleration phase during COD-sprints that may not be compensated for by the increased requirement of the reacceleration phase. On the other hand, 20-m sprints with one COD may elicit a substantially greater activity of VL and BF than a 20-m sprint in straight-line. Finally, the actual speed reached before the COD may have only a limited effect on metabolic and lower limb muscular activity demands. The presence of COD also highlights the dissociation between metabolic demands and muscle activity, which directly questions the use of metabolic power as a single measure of running load in soccer.

Acknowledgments

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5

Fig. Legends

Fig. 1. Experimental set up with the new timing methodology combining two speed guns synchronized. See methods for details.

Fig. 2: Estimated energy expenditure of sprints with (45° or 90°) or without (i.e., straight-line, SL) one change of direction (COD); 90°$_{25}$: 25-m sprint with one 90°-COD. The upper panel represents the standardized difference (Std Diff) between COD- and SL sprints. Since 90°$_{25}$ vs. 20-m SL sprints could not be properly compared (i.e., differences in both running time and distance), their standardized difference (black circle) was not provided. The number of '*' and '†' refers to possible, likely, very likely and almost certain between-sprints differences versus the 45°-COD sprint trial, and within-sprint differences vs. the acceleration phase, respectively. The associated number refers to the magnitude of the difference, with 1 standing for small, 2 for moderate, 3 for large and 4 for very large magnitude.

Fig. 3: Relationship between acceleration and metabolic power

Fig. 4: Electromyography amplitude (RMS) of 2 muscles during sprints with (45° or 90°) or without (i.e., straight-line, SL) one change of direction (COD). The upper panel concerns the vastus lateralis muscle and the lower panel, the biceps femoris muscle. 90°$_{25}$: 25-m sprint with one 90°-COD. The number of '*' and '†' refers to possible, likely, very likely and almost certain difference versus straight-line and 45°-COD sprints, respectively. The associated number refers to the magnitude of the difference, with 1 standing for small, 2 for moderate, 3 for large and 4 for very large magnitude.

Fig. 5: Electromyography amplitude (RMS) of vastus lateralis and biceps femoris muscles and speed profiles during sprints with (45° or 90°) or without (i.e., straight-line, SL) one change of direction (COD). 90°$_{25}$: 25-m sprint with one 90°-COD. The medial panel represents the standardized difference (Std Diff) of RMS between COD- and SL-sprints. The number of '*' and '†' refers to possible, likely, very likely and almost certain difference versus straight-line and 45°-COD sprints, respectively.

Fig. 6: Metabolic power/electromyography amplitude (RMS) ratio of sprints with (45° or 90°) or without (i.e., straight-line (SL)) one change of direction (COD). 90°$_{25}$: 25-m sprint with one 90°-COD; BF: biceps femoris; VL: vastus lateralis. The number of '*' and '†' refers to possible, likely, very likely and almost certain difference versus straight-line and 45°-COD sprints, respectively. The associated number refers to the magnitude of the difference, with 1 standing for small, 2 for moderate, 3 for large and 4 for very large magnitude.
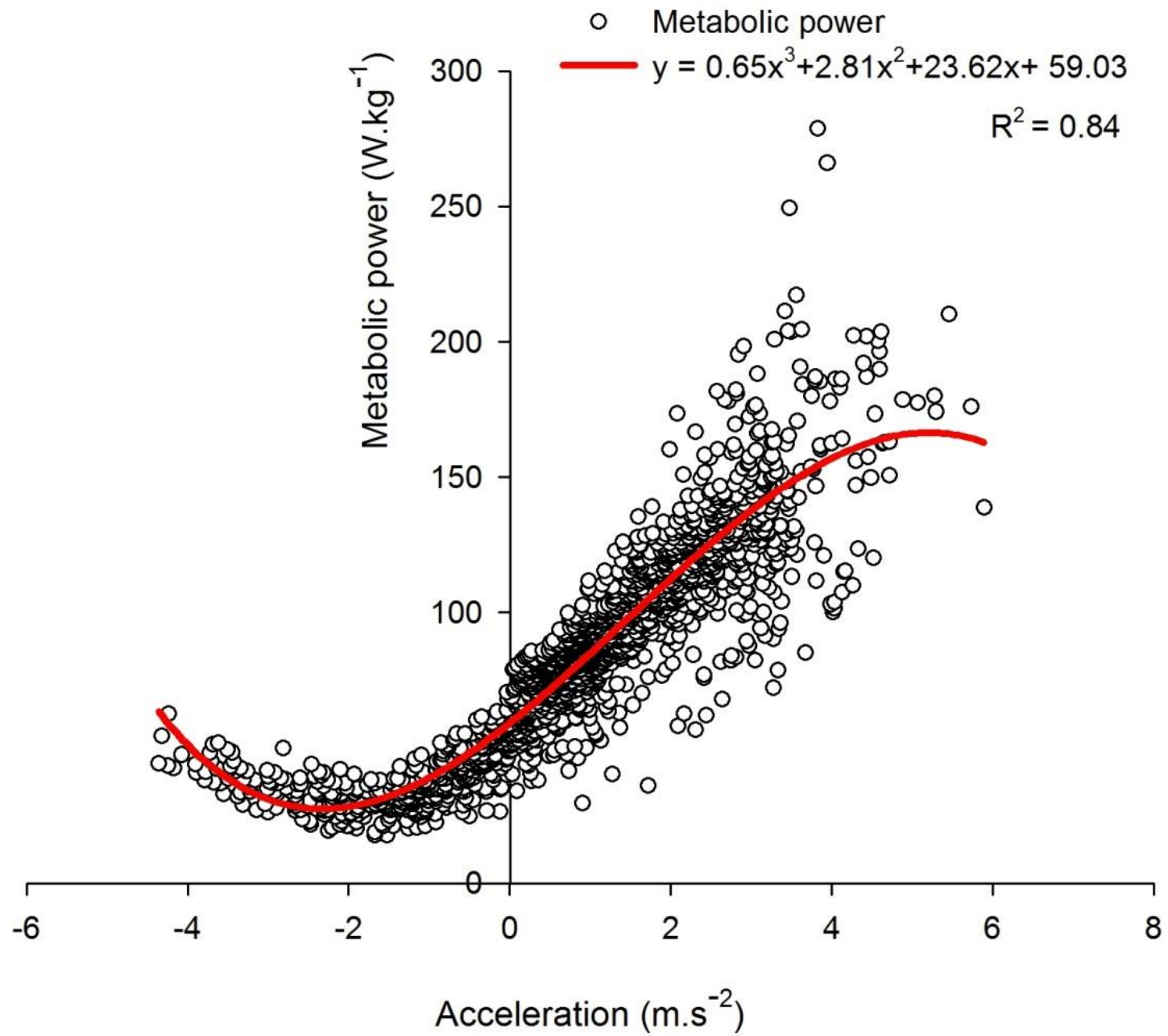
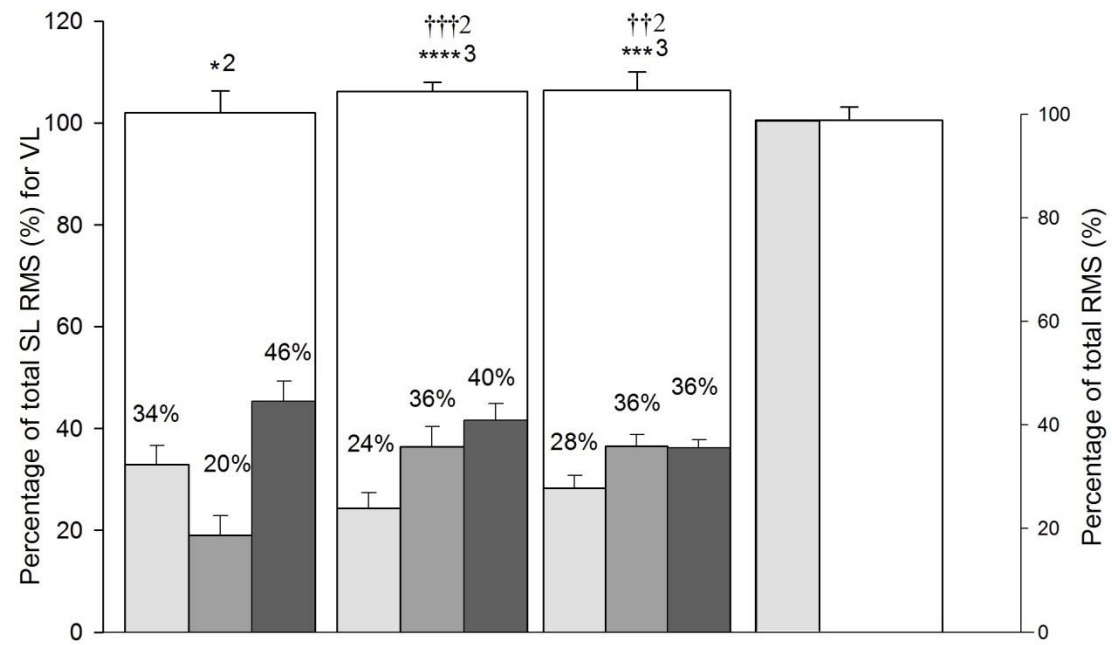**Fig. 7:** Metabolic power/electromyography amplitude (RMS) ratio during the different phases of sprints with (45° or 90°) or without (i.e., straight-line (SL)) one change of direction (COD). 90°$_{25}$: 25-m sprint with one 90°-COD; BF: biceps femoris; VL: vastus lateralis. The number of '*' and '†' refers to possible, likely, very likely and almost certain difference versus straight-line and 45°-COD sprints, respectively. The associated number refers to the magnitude of the difference, with 1 standing for small, 2 for moderate, 3 for large and 4 for very large magnitude

Supporting information

S1 Table. Estimated energy expenditure of sprints with (45° or 90°) or without one change of direction

S2 Table. Estimated energy expenditure of sprints with change of direction-time-adjusted straight-line distances

S3 Table. Sprints performance with (45° or 90°) or without one change of direction

S4 Table. Change of direction-time-adjusted straight-line distances

S5 Table. Electromyography amplitude of Vastus Lateralis muscle during sprints with (45° or 90°) one change of direction

S6 Table. Electromyography amplitude (RMS) of Biceps Femoris muscle during sprints with (45° or 90°) one change of direction

S7 Table. Metabolic power/electromyography amplitude (RMS) ratio of sprints with (45° or 90°) or without one change of direction

S8 Table. Metabolic power/electromyography amplitude (RMS) ratio during the different phases of sprints with (45° or 90°) one change of direction
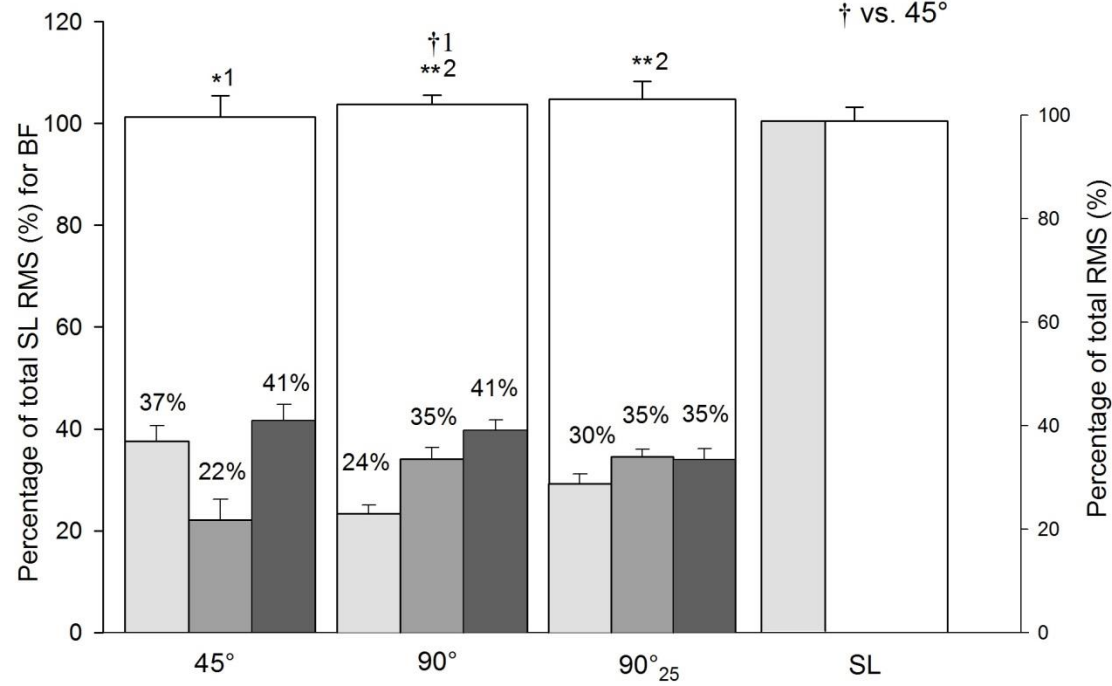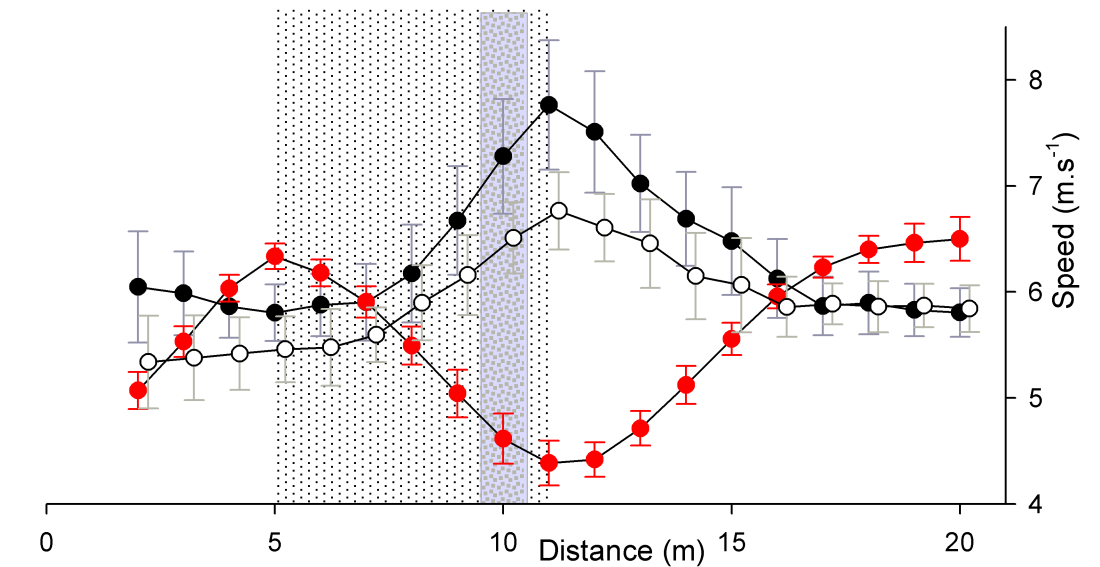
Finish

Finish

10-m Sprint SL

10-m Sprint 45°

Finish

10-m Sprint 90°

Radar 2 (90°)

Radar 2 (45°)

10-m Sprint

Jog

Start

Radar 1

△ Timing gates

● Cone

Top panel y-axis (left): Percentage of total SL RMS (%) for VL
Top panel y-axis (right): Percentage of total RMS (%)

Top panel annotations:
*2 (45°)
†††2 / ****3 (90°)
††2 / ***3 (90°25)

Percentages (top panel):
45°: 34%, 20%, 46%
90°: 24%, 36%, 40%
90°25: 28%, 36%, 36%

* vs. SL
† vs. 45°

Bottom panel y-axis (left): Percentage of total SL RMS (%) for BF
Bottom panel y-axis (right): Percentage of total RMS (%)

Bottom panel annotations:
*1 (45°)
†1 / **2 (90°)
**2 (90°25)

Percentages (bottom panel):
45°: 37%, 22%, 41%
90°: 24%, 35%, 41%
90°25: 30%, 35%, 35%

X-axis: 45°   90°   90°25   SL