Kinematic algorithm to determine the energy cost of running with changes of direction

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KINEMATIC ALGORITHM TO DETERMINE THE ENERGY COST OF RUNNING WITH CHANGES OF DIRECTION

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ABSTRACT

Changes of direction (CoDs) have a high metabolic and mechanical impact in field and court team sports, but the estimation of the associated workload is still inaccurate. This study aims at validating an algorithm based on kinematic data to estimate the energy cost of running with frequent 180°-CoDs.

Twenty-six physically active male subjects (22.4±3.2 years) participated in two sessions: (1) maximum oxygen uptake ($\dot{V}O_{2,max}$) and maximal aerobic speed (MAS) test; (2) 5-m continuous shuttle run (two 5-min trials at 50% and 75% MAS, 6-min recovery). In (2), full-body 3D-kinematics and $\dot{V}O_2$ were simultaneously recorded. Actual cost of shuttle running (C_{meas}) was obtained from the aerobic, anaerobic alactic and lactic components.

The proposed algorithm detects "braking phases", periods of mostly negative (eccentric) work occurring at concurrent knee flexion and ground contact, and estimates energy cost (C_{est}) considering negative mechanical work in braking phases, and positive elsewhere.

At the speed of, respectively, 1.54±0.17 and 1.90±0.15 $m \cdot s^{-1}$ (rate of perceived exertion: 9.1±1.8 and 15.8±1.9), C_{meas} was 8.06±0.49 and 9.04±0.73 $J \cdot kg^{-1} \cdot m^{-1}$. C_{est} was more accurate than regression models found in literature ($p<0.01$), and not significantly different from C_{meas} ($p>0.05$; average error: 8.3%, root-mean-square error: 0.86 $J \cdot kg^{-1} \cdot m^{-1}$).

The proposed algorithm improved existing techniques based on CoM kinematics, integrating data of ground contacts and joint angles that allowed to separate propulsive from braking phases. This work constitutes the basis to extend the model from the laboratory to the field, providing a reliable measure of training and matches workload.

Keywords: metabolic cost, energy expenditure, shuttle run, eccentric work, mechanical work, workload, team sports.

ABBREVIATIONS

C_{meas}: energy cost of shuttle running, measured ($J \cdot kg^{-1} \cdot m^{-1}$)

C_{est}: energy cost of shuttle running, estimated ($J \cdot kg^{-1} \cdot m^{-1}$)

CoD: change of direction

CoM: body centre of mass

E^{+}_{ext}: positive external mechanical energy ($J \cdot kg^{-1}$)

E^{-}_{ext}: negative external mechanical energy ($J \cdot kg^{-1}$)

$\dot{E}_{meas}$: metabolic power, measured ($W \cdot kg^{-1}$)

$[La^{-}]_b$: lactate concentration (mM)

MAS: maximal aerobic speed ($m \cdot s^{-1}$)

RER: respiratory exchange ratio

SMR: standing metabolic rate ($ml \cdot kg^{-1} \cdot min^{-1}$)

v_{CoM}: centre of mass horizontal speed ($m \cdot s^{-1}$)

v_{sh}: nominal horizontal shuttle speed ($m \cdot s^{-1}$)

v_{max}: maximal horizontal shuttle speed ($m \cdot s^{-1}$)

$\dot{V}O_2$: Oxygen uptake ($ml \cdot kg^{-1} \cdot min^{-1}$)

W_{ext}: external mechanical work (J)

W^{+}_{ext}: positive external mechanical work (J)

W^{-}_{ext}: negative external mechanical work (J)

W_{int}: internal mechanical work (J)

η^{+}: positive mechanical work muscular efficiency

η^{-}: negative mechanical work muscular efficiency

1 Introduction

Team sports players frequently perform power actions with short recovery periods like shuttle runs, changes of direction (CoD) and sprints. Turns, or 180°-CoDs, imply eccentric muscular efforts and increase the energy cost relative to linear running (Dellal et al., 2010), providing a substantial contribution to the physiological demands of exercise (Hatamoto et al., 2013).

The acceleration/deceleration dynamics of repeated CoDs produce high levels of metabolic and mechanical load (Osgnach et al., 2010), reflected by increased markers of muscular damage following activities replicating match play (Silva et al., 2013). Understanding the energetics of CoDs is useful to assess actual energy requirements of exercise, impacting upon injury prevention strategies, nutrition, training plans, and in turn the health of the athletes.

Historically, mechanical work of locomotion was investigated in linear walking and running, and the relationship between mechanical work and metabolic energy has been addressed (Cavagna and Kaneko, 1977): some approaches focused on external work, others introduced internal (Purkiss and Robertson, 2003) and collisions-related negative work (Donelan et al., 2002; Ruina et al., 2005). However, the feasibility of these methods is unclear when applied to CoDs, and their practical use remains difficult.

Methods of energy cost estimation during sprint running were introduced assuming forward accelerations-decelerations as primary drivers of energy cost (di Prampero et al., 2014). Body orientation on an inclined terrain is similar to that of accelerated running at constant speed. However, when applied to shuttle running, this approach underestimated the actual load by ~15%, and was highly sensitive to tracking technology and signal filtering (Stevens et al., 2015). Further, the energy required to decelerate the body was not considered, while in CoDs it cannot be neglected, especially with short distances (Neptune et al., 2004).

Recently, Zamparo and colleagues (2015) made significant advances investigating muscular efficiency of acceleration/deceleration phases in 5-m shuttle runs. They proposed a linear equation to estimate the related metabolic cost which was not, however, fully applicable to longer shuttle runs and whose accuracy depended on running technique (Zamparo et al., 2015). In their following, groundbreaking article, the same group computed positive, negative and internal work in 5-m shuttle run (Zamparo et al., 2016). Although it was the first study comparing measured metabolic cost and its estimation with motion capture systems, kinematic and metabolic data were recorded in separate sessions.

Therefore, the aim of the present work is to establish a kinematic-based algorithm to determine the energetic cost of running with frequent 180°-CoDs. We hypothesize that if such algorithm succeeds in estimating the energy expenditure of many consecutive CoDs, it would be the first step to estimate the energy demand of also the spare, non-cyclic turns typical of team-sports. In particular, since energy expenditure is associated with both positive and negative muscular work, the role of the latter should be considered (Zamparo et al., 2016). This work may also constitute a preliminary methodological framework for an application to wearable technologies, allowing for reliable on-the-field energy cost estimation.

2 METHODS

2.1 PARTICIPANTS

Twenty-six male sports science students (22.4±3.2 years) participated in the study (Table 1). According to the International Physical Activity Questionnaire (Craig et al., 2003), physical activity level was ‘high’ for 22/26 participants and ‘moderate’ for the others; 25 participants coped well with the entire protocol. For technical issues, one participant did not complete the second trial.

All subjects signed written informed consent after detailed explanation of aims, benefits and risks of this investigation, that was approved by the Institutional Ethics Committee (n.1/16) and met the current ethical standards in sports research.

2.2 PROCEDURES

This observational study involved two sessions on separate days: 1) maximum oxygen uptake ($\dot{V}O_{2,max}$) and maximal aerobic speed (MAS) were obtained with an incremental discontinuous square-wave test on a treadmill (Esposito et al., 2004); 2) shuttle-run test: after the recording of standing metabolic rate (SMR, 60-s average), subjects completed two 5-minutes trials of 5-m shuttle running at an average shuttle speed (v_{sh}) of 50% and 75% of their MAS, each followed by a recovery period of at least 6-min, till the HR returned to baseline values. The selected shuttle speeds allowed to evaluate the algorithm in medium and intense exercise conditions (Ciprandi et al., 2017).

During the experiment, a metronomic acoustic device helped participants to keep the selected running speed. In the days preceding the shuttle trial, participants were carefully trained by an experience operator to perform turns with the sidestep cut technique: the pivoting foot (alternated to avoid unilateral overloading) should land perpendicularly to the running direction; the outgoing path proceeds away from the support-leg side (Schot et al., 1995).

In both sessions, $\dot{V}O_2$ was measured with a portable metabolimeter (K4b^2, Cosmed, Rome, Italy). In the recovery period, peak blood lactate concentration ($[La^-]_b$) was determined with a portable analyzer (LacPro, BST, Berlin, Germany) every two minutes, till a decrease in the measure. After each trial, subjects provided a rating of general, muscular and respiratory perceived exertion (RPE, 6-20 Borg scale).

During the entire shuttle tests (session 2), simultaneously with the metabolic measurements, the instantaneous positions of 18 reflective markers (C7 and sacrum; right and left acromia, olecranons, radius styloid processes, ASISs, femoral lateral epicondyles, lateral malleoli, calcanei, foot – corresponding to the 5th metatarsal heads) were recorded at 60 Hz with an optical motion capture system (BTS, Milano, Italy). Before trials, participants were acquired for five seconds in the anatomical position, setting a reference for anatomical angles and ground-contact thresholds.

2.3 DATA PROCESSING

Custom Matlab (Mathworks Inc., Natwick, USA) routines were developed.

METABOLIC DATA

Spurious-breath data were removed when exceeding ±1.96 local standard deviations of the absolute difference between raw data and the fitting spline curve. The energy cost of shuttle running (C_{meas}, $J \cdot kg^{-1} \cdot m^{-1}$) was obtained from the sum of aerobic, anaerobic alactic and anaerobic lactic energy expenditure (Buglione and di Prampero, 2013). The aerobic component was the integral of $\dot{V}O_2$ from the exercise onset to its end, subtracting pre-exercise SMR. The anaerobic alactic component, representing the fast component of the alactic O_2 debt, was obtained from the $\dot{V}O_2$ kinetics during recovery, computing the area between oxygen uptake (1st-to-6th minutes of recovery) and the line interpolating the 4th and 6th minutes of recovery (Figure 1). The oxygen energy equivalent was computed from: $\dot{V}O_2 \cdot (4.94 \cdot RER + 16.04)$ $J \cdot ml \cdot O_2^{-1}$. The lactic energy equivalent was 3.3 $ml \cdot kg^{-1} \cdot mM^{-1}$ (di Prampero and Ferretti, 1999).

KINEMATIC DATA

Raw coordinates were filtered with a Butterworth zero-lag, 2nd-order low-pass filter. The cut-off frequency (f_{cut}=15 Hz) was chosen following a sensitivity analysis that showed a substantial independence of the final estimated energy cost for f_{cut}>10 Hz (unpublished results). Center-of-mass (CoM) kinematics was computed (Mapelli et al., 2014); knee flexion-extension angle was the reciprocal rotation of thigh and shank local coordinate systems (Euler ZYZ convention). CoM external mechanical energy (E_{ext}) was computed at each time frame as the sum of potential and kinetic energy (Cavagna and Kaneko, 1977).

CoM speed (v_{CoM}) was the CoM horizontal path throughout the entire exercise (d_{CoM}) divided by the exercise time; maximal speed (v_{max}) was the peak value of the time derivative of CoM horizontal trajectory.

2.4 Metabolic cost estimation

The proposed estimation algorithm was based on the following assumptions:

1. Body mass is located in the CoM.
2. Although part of the decrease/increase of total energy is caused by tendon stretch and recoil during running (Purkiss and Robertson, 2003), metabolic energy is expended both for positive (concentric) and negative (eccentric) work (Kuo, 2007), the latter playing an important role in decelerations (Dellal et al., 2010).
3. The efficiency of positive and negative muscular work is $\eta^{+} = 25\%$ and $\eta^{-} = -120\%$, respectively (Cavagna and Kaneko, 1977; Kuo, 2007).
4. During running, more than 55% of total negative work is done at the knee, since when producing braking forces, muscles at this joint work as stabilizers and shock absorbers (hips and ankles contribution to negative work is 25% and 10%, respectively (Purkiss and Robertson, 2003)).

The estimation algorithm relies on the detection of "braking phases", time windows where knee extensors perform mostly negative (eccentric) work. Based on the previous assumptions, we located braking phases when a knee is flexing and the same limb is touching the ground (Figure 2). Knee flexion was determined at time instants (t) of negative knee-flexion angular velocity ($\omega_{flex}(t)$< 0). Ground contact frames where those in which the vertical coordinate of the foot (y_f) or the calcaneus marker (y_c) were below a threshold ($y_{f,th}$ and $y_{c,th}$, respectively, i.e. the height of corresponding markers in the static acquisition plus a 0.75-mm offset, the markers' radius). For each limb, the logical vector locating braking frames (*Bf*) was:

$$Bf(t) = \big(\omega_{flex}(t) < 0\big)\textbf{and}\big([y_f(t) \le y_{f,th}]\textbf{or}[y_c(t) \le y_{c,th}]\big) \quad (1)$$

Braking frames were the sum of right and left logical vectors: $Bf(t)=Bf_{right}(t)$ **or** $Bf_{left}(t)$.

The overall estimated energy cost (C_{est}) was obtained as the sum of negative decrements of E_{ext} (ΔE^{-}_{ext}) in braking phases, and positive increments of E_{ext} (ΔE^{+}_{ext}) elsewhere, divided by the related efficiency and d_{CoM}:

$$C_{est} = \left(\frac{\sum \Delta E^{+}_{ext}|_{\overline{Bf}}}{\eta^{+}} + \frac{\sum \Delta E^{-}_{ext}|_{Bf}}{\eta^{-}}\right)\Big/ d_{CoM} \qquad (2)$$

$W^{+/-}_{ext}$ is the sum of changes in $\Delta E^{+/-}_{ext}$. The amount of $W^{+/-}_{ext}$ considered by the model and required to perform a single CoD was computed; a CoD was intended as the 2.5+2.5-m path between the halfway of two consecutive shuttles (see Figure 2).

Lastly, results were compared with the energy cost obtained with the linear model proposed by Zamparo et al. (2015):

$$C_{lm}=11.94\ v_{CoM}-12.82. \qquad (3)$$

2.5 Statistical analysis

An *a priori* power analysis on preliminary data showed that a sample size of 24 participants would provide a statistical power of 90%, an effect size of 0.5 and an alpha of 0.05.

Differences between cardio-metabolic parameters of the two shuttle trials were assessed with paired Student's t-tests. To test differences among C_{meas}, C_{est} and C_{lm}, two-factors (3 methods×2 speeds) ANOVA with repeated measures was conducted. When significant effects were found, we performed Bonferroni-adjusted post-hoc comparisons. Root-mean-square error (RMSE) and Bland-Altman plot were used to evaluate the accuracy of the estimation.

The relationship between C_{meas} vs. speed and C_{meas} vs. C_{est} were assessed with Pearson's correlation coefficient (r). Cohen's d effect size measured the practical effects of differences: ranges of $d<0.5$, $0.5\le d\le 0.8$ and $d>0.8$ were considered low, moderate and large effects, respectively. Significance level was set at α=5%.

3 Results

The exercise intensity in the two trials was markedly different (Table 2), being $\dot{V}O_2$, heart-rate, $[La^-]_b$ and RPE significantly higher at 75% MAS.

C_{meas} ranges were 7.19-8.99 (50% MAS) and 7.49-10.49 $J \cdot kg^{-1} \cdot m^{-1}$ (75% MAS). The energy costs were significantly higher at 75% MAS (+12%, +14%, and +62% for C_{meas}, C_{est} and C_{lm}, $p<0.001$). C_{lm} was significantly lower than C_{meas} at 50% and higher at 75% MAS (–15% and +23%, respectively, $p<0.01$); a correlation of $r=0.756$ and no significant differences were found between C_{meas} and C_{est}, nor as a function of the trial (speed×method interaction, $p=0.213$). C_{meas} was moderately correlated to speed ($r=0.63$, $p<0.001$, Figure 3).

v_{CoM} was lower than nominal speed v_{sh}, as body CoM travels less than 2.5+2.5 m at each CoD. Actual travelled CoM path was 9.15% lower ($p<0.001$) at 75% MAS. Almost identical values of total W^+_{ext}/CoD and W^-_{ext}/CoD were obtained. The fraction of total external work considered by the model was substantially unchanged among the two trials (82% of W^+_{ext}, 70% of W^-_{ext}).

The proposed method slightly overestimated C_{meas}: absolute error of 8.3% (5.7%), RMSE of 0.86 $J \cdot kg^{-1} \cdot m^{-1}$ (Figure 4). The estimation error was weakly and not significantly dependent from the energy cost ($r=0.27$, $p=0.064$). Table 3 reports the estimation errors of C_{est} and C_{lm} referred to C_{meas}: a small-to-medium effect size was measured for all comparisons except C_{lm} vs. C_{meas} at 50% MAS, showing a large effect.

4 Discussion

We developed an algorithm to estimate the energy cost of running with 180° CoDs, combining estimates of positive and negative mechanical work with actual metabolic output.

In general, on-the-field estimation of the metabolic demands in team sports is difficult due to lack of accurate and practical methods, and those that have been used present limitations (Walker et al., 2014): (i) video analysis is labor-intensive and provides crude measurements of energy expenditure; (ii) Global Positioning System is prone to considerable errors in measuring accelerations at high speeds; (iii) heart-rate estimated the energy expenditure of professional soccer and rugby players with an error of 15–20%; (iv) inertial sensors are a simple and non-intrusive solution, but existing methods reported errors higher than 10%, even not accounting for actions involving vertical CoM displacements (Walker et al., 2014) or lateral accelerations.

Our approach combined CoM kinematics with ground contacts and knee flexion angles to estimate the energy cost of an ecologic exercise. This allowed to separate propulsive from braking phases and ensured physical plausibility, thus reducing the estimation error.

4.1 Continuous changes of direction and energy expenditure

Short runs with continuous accelerations–decelerations break the kinetics of the $\dot{V}O_2$ and prevents the attainment of steady-state, impairing the estimation of the corresponding energy expenditure (di Prampero et al., 2014). Exploiting the approach that Buglione and di Prampero (2013) applied to intermittent shuttle run, such intrinsic non-steady-state condition was overcome considering 5-minutes windows of continuous shuttle running. Thus, while the energy expenditure during a unique CoD cannot be easily determined, many continuous CoDs led to a "macroscopically steady" cardiorespiratory and metabolic state (Zamparo et al., 2014, 2015). Although 5-minutes of continuous shuttle running rarely occurs in competitions, physiological parameters matched the activity profiles of team sports (Ciprandi et al., 2017; Spencer et al., 2005), where athletes perform at an average intensity of 70-80% of $\dot{V}O_{2,max}$ (Bangsbo, 1994).

As expected, C_{meas} was significantly higher at 75% compared to 50% MAS, confirming that the energy cost of running with CoDs increases with running velocity (Figure 3) (Stevens et al., 2015; Zamparo et al., 2014).

A word of caution should be entered regarding the direct comparison of energy costs in the current study and those by Zamparo et al. (2015, 2014). Although apparently assessing similar topics, the exercise protocols were substantially different. In our study, shuttles were performed continuously (each 5+5 m run involved two accelerations and two decelerations), while in Zamparo et al. maximal shuttle runs were followed by 30-s recovery (two accelerations and one deceleration each 5+5 m). This explains why our speed values may appear low for a running action, as the additional braking action (repeated 22-30 times/minute) inevitably reduced the average speed. Most important, in our study a higher number of eccentric actions per 5+5-m run was performed. It is known that, for a given mechanical power output, eccentric exercise requires a lower metabolic demand than concentric exercise (Douglas et al., 2016), and that a dissociation exists in CoDs between metabolic and muscle activity (Hader et al., 2016). Therefore, it is reasonable that our protocol, with a higher eccentric component, required less energy per unit distance. Coherently, although the energy cost of locomotion was only 12% higher at 75% MAS, our study showed high levels of muscular RPE (~17) and $[La^-]_b$ (9 mM at v_{sh}=2.9 m·s^{-1}, compared to 3.5 mM reported by Zamparo et al. (2015) at 3.5 m·s^{-1}).

4.2 ENERGY COST ESTIMATION ALGORITHM

Methods to estimate the energy cost of locomotion were historically based on inverted pendulum (walk) and spring (run) analogies (Cavagna and Kaneko, 1977). However, the classic approach of integrating increments of E_{ext} is not applicable to CoDs, as the energetics of CoDs is incomplete without consideration of negative work, and only part of positive work is related to metabolic energy expenditure (Van Ingen Schenau et al., 1997). Indirect approaches based on 2D CoM kinematics underestimated the actual load for shuttle runs shorter than 20 m and speeds lower than 3.3 m·s^{-1} (Stevens et al., 2015; Zamparo et al., 2014).

The proposed algorithm distinguished the contribution of positive work in propulsive phases from negative work in braking phases. Overall, the amount of positive and negative work was almost equal, since globally the number of accelerations and decelerations was the same. Average W_{ext}^{+} per unit distance was 1.71 and 2.01 J·kg^{-1}·m^{-1} in the two trials, respectively. Zamparo et al. (2016) found values from 2.1 to 2.6 J·kg^{-1}·m^{-1} (speed: 2.2 to 3.3 m·s^{-1}). This difference can be justified by the different exercise protocol and the lower shuttle speed in the present study.

Although during double-support legs perform simultaneously positive and negative work (Kuo, 2007), we regarded at braking phases as windows of "mostly negative" work. Moreover, excluding W_{ext}^{+} from braking phases, the algorithm implicitly takes muscles/tendons stiffness into account. These structures act as temporary stores of mechanical energy: some positive work is absorbed in eccentric and then released in concentric conditions, thus part of W_{ext}^{+} is performed passively by series of elastic elements, rather than by active contractile elements (Kuo, 2007). The impact of negative work included in the model was not negligible (W_{ext}^{-} ranged from 1.54 to 1.70 J·kg^{-1}·m^{-1}), coherently with the important role played by eccentric phases in turns (Hader et al., 2016; Zamparo et al., 2016, 2015).

The proposed algorithm slightly overestimated C_{meas} and was substantially independent from running speed in the considered range (i.e. there was not systematic error). Compared to the linear model by Zamparo et al. (2015), the proposed algorithm returned a significantly lower absolute error (Table 3).

Some substantial novelties were introduced. First, metabolic and kinematics data were acquired simultaneously. Thus, the mechanical work computations exactly refer to oxygen uptake measurements, favoring the reliability of the estimation. Second, the algorithm returned a good estimation at both low and high exercise intensity. Third, rather than a linear equation, we developed a realistic biomechanical model based on 3D kinematics. This point is crucial, because it does not limit the method to shuttle run. In this study, shuttle was used to extensively analyze CoDs, but the model is potentially able to capture the metabolic contribution of movements like jumps, cutting maneuvers and other locomotor actions.

4.3 LIMITATIONS

Negative work performed by the shoes-floor friction and in the damped motion of muscles and viscera is difficult to quantify theoretically and empirically (Kuo, 2007). Additionally, many physiological factors may lead to variability in computing mechanical work, like fitness level, baseline subtractions, structural/technical differences, and more importantly the efficiency of mechanical to metabolic energy conversion.

The contribution of internal energy was not calculated, while it can represent a consistent fraction of total mechanical work (0.5-2.5 $J \cdot kg^{-1} \cdot m^{-1}$) (Zamparo et al., 2016), especially at high shuttle speed. Two reasons explain why our method provided accurate results, even not including W_{int}: 1) W_{ext} was overestimated; 2) muscular efficiency values were higher than real. In our model, we took average constants, while each individual has a unique set of coefficients, which also depend on speed and exercise condition. For instance, Minetti et al. (2002) reported an efficiency of -1.05 ($\eta-$) for downhill and 0.22 ($\eta+$) for uphill running; it was also proposed that, during a CoD, co-contractions and isometric contractions can reduce efficiency (Cavanagh and Kram, 1983).

During match play, CoDs are mostly unplanned, while our protocol involved repeated pre-planned turns. The continuous repetition of the same movement pattern could have produced an increasing neuromuscular economy.

Lastly, the results of the current study should be considered limitedly to this specific male sample. Sex-specific features due to different pelvis and lower limbs biomechanics, and/or sport-specific adaptations to a specific discipline have to be selectively addressed.

4.4 Practical implications

The benefit of the proposed algorithm is three-fold. First, for researchers interested in estimating energy cost from kinematic data within a motion capture laboratory. Second, for wearable devices developers, it constitutes a framework for a reliable energy-cost estimation tool. Algorithm improvements can include individualized characterization of muscular efficiency, reduction of considered W_{ext} by excluding airborne phases, W_{int} computation. However, the model has the advantage of a relative simplicity. This allows future investigators to develop a similar algorithm based on wearable sensor data to produce equivalent output: recent papers showed that algorithms merging magnetic, inertial and eventually GPS data from multi-sensor systems can potentially provide the information required to run the algorithm in outdoor conditions (Riaz et al., 2015; Wouda et al., 2016).

Third, for sport scientists and trainers, knowing the actual workload of exercise would help to produce recommendations of appropriate nutritional intake, optimize performance and sustain optimal growth and development in youth (Briggs et al., 2015). In addition, turns and cutting maneuvers are high-risk situations for the integrity of knee ligaments (Nyland et al., 1997) and fatigue has a detrimental effect on neuromuscular control of lower limbs (Read et al., 2016). Understanding the relationship between the energy cost of 180°-directional changes and injury risk may help in preventing unsafe exercise conditions.

5 Conclusion

To improve the estimation of the energetic requirements of running with 180°-CoDs, we introduced an algorithm based on kinematic data. Even though it does not describe the complex mechanisms at the molecular and fiber-level, the model offers a conceptual description of the energetics of turns, and a low estimation error with respect to the simultaneous metabolic cost.

The model is not limited to the estimation of energy cost of shuttle running; rather, can potentially predict the energy cost of jumps and any kind of change of direction. Thus, the algorithm could be developed for wearable multi-sensor systems for a reliable on-the-field workload estimation.

Conflict of interest statement

No external funding was received for this study. The authors have no financial interests or other forms of conflicts of interest.

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TABLES

Table 1. Participants' anthropometric and physiological data.

Characteristic	Unit	Mean	SD	Range	
Age	Years	22.4	3.2	18.0	33.5
Body mass	kg	74.2	7.3	63.0	91.5
Height	m	1.76	0.06	1.61	1.86
BMI	$kg \cdot m^{-2}$	23.9	1.7	20.7	27.6
SMR	$ml \cdot kg^{-1} \cdot min^{-1}$	5.7	0.9	3.9	7.5
$\dot{V}O_{2,max}$	$ml \cdot kg^{-1} \cdot min^{-1}$	52.4	7.6	33.8	72.5
MAS	$m \cdot s^{-1}$	4.01	0.37	2.96	4.69
PA	METS $min \cdot week^{-1}$	4161	1558	1305	7704

BMI: body mass index; SMR: standing metabolic rate; $\dot{V}O_{2,max}$: maximum Oxygen uptake; MAS: maximal aerobic speed; PA: Physical Activity, from the International Physical Activity Questionnaire.

Table 2. Shuttle and exercise-related data during the two trials.

		Trial 1 (50% MAS)		Trial 2 (75% MAS)	
Variable	Unit	Mean	SD	Mean	SD
v_{sh}	$m \cdot s^{-1}$	2.03*	0.21	2.92	0.27
v_{CoM}	$m \cdot s^{-1}$	1.54*	0.17	1.90	0.15
v_{max}	$m \cdot s^{-1}$	2.19*	0.26	3.07	0.25
$\dot{V}O_2$	$ml \cdot kg^{-1} \cdot min^{-1}$	35.8*	6.6	46.1	6.5
HR	bpm	155*	14	185	8
$[La^-]_b$	mM	2.61*	1.01	9.78	3.05
RPE general	-	9.1*	1.8	15.8	1.9
RPE respiratory	-	9.5*	2.2	15.6	2.6
RPE muscular	-	8.8*	2.1	16.6	2.1
nCod/min	min^{-1}	22.1*	2.7	29.9	2.9
CoM distance/ CoD	M	4.13*	0.12	3.78	0.04
W^+_{ext}/ CoD	$J \cdot kg^{-1}$	8.55	0.95	9.28	1.40
W^-_{ext} / CoD	$J \cdot kg^{-1}$	8.53	0.99	9.29	1.43
$W^+_{ext,\ in\ model}$	%	81.8	5.6	81.6	4.5
$W^-_{ext,\ in\ model}$	%	73.5	7.8	68.9	8.5
$\dot{E}_{meas}$	$W \cdot kg^{-1}$	12.3*	1.9	16.8	2.2
C_{meas}	$J \cdot kg^{-1}\ m^{-1}$	8.06*	0.49	9.04	0.73
C_{est}	$J \cdot kg^{-1} \cdot m^{-1}$	8.26*$^{\#}$	0.82	9.45$^{\#}$	0.81
C_{lm}	$J \cdot kg^{-1} \cdot m^{-1}$	6.86*§	1.69	11.12§	1.90

$\dot{V}O_2$: Oxygen uptake during the last minute; HR: heart rate during the last minute; $[La^-]_b$: blood lactate concentration; RPE: rate of perceived exertion (6-20); nCoD/min: number of changes of direction (2.5+2.5 m) per minute; $W_{ext,\ model}$; percentage of Wext included in the model; $\dot{E}_{meas}$: measured metabolic power; $C_{meas/est}$: measured/estimated energy cost; C_{lm}: energy cost estimated with the linear model proposed in (Zamparo et al., 2015).

* significantly different ($p<0.05$) from 75% MAS; § significantly different ($p<0.01$) from C_{meas}. # significantly different from C_{lm} ($p<0.05$).

Table 3. Performance of the estimation method, measured as mean (SD) absolute and percentage error relative to measured energy cost.

		Mean absolute error ($J \cdot kg^{-1} \cdot m^{-1}$)	Error (%)	ES
50% MAS	C_{est}	0.62 (0.46)	7.3 (5.6)	0.30
	C_{lm}	1.86 (1.66)	23.5 (22.5)	0.87
75% MAS	C_{est}	0.83 (0.49)	9.3 (5.3)	0.51
	C_{lm}	2.29 (1.59)	26.1 (18.6)	0.39

ES: effect size; C_{est}: estimated energy cost; C_{lm}: energy cost estimated with the linear model proposed in (Zamparo et al., 2015).

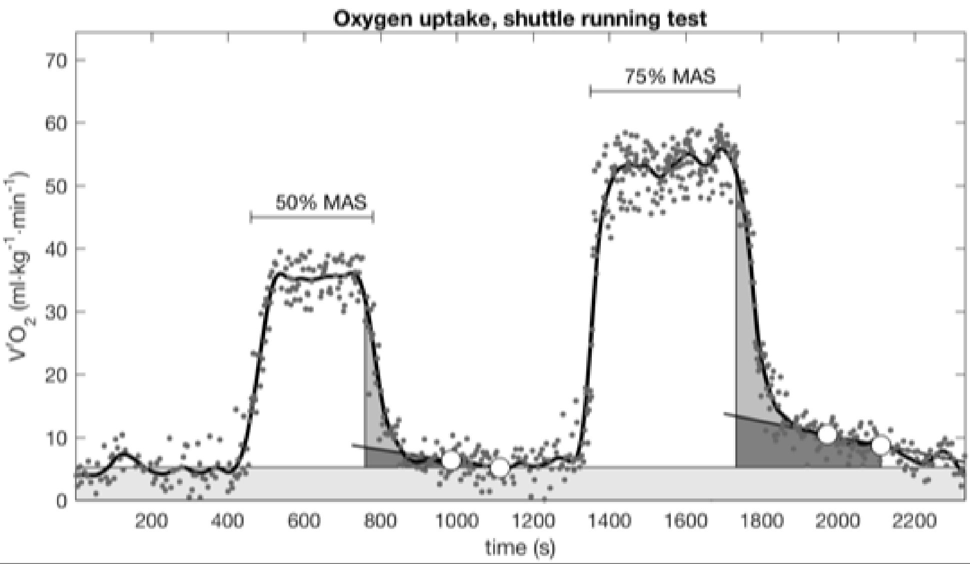
FIGURES CAPTIONS

Figure 1: One subject's oxygen kinetic during the shuttle run test. Raw metabolimeter data (dots) were interpolated with splines (continuous curve); white circles are at the 4th and 6th minutes of recovery (for both trials). The light gray area in the recovery phase is the anaerobic alactic component (fast recovery phase). The shaded bottom rectangle represents the standing metabolic rate (SMR).

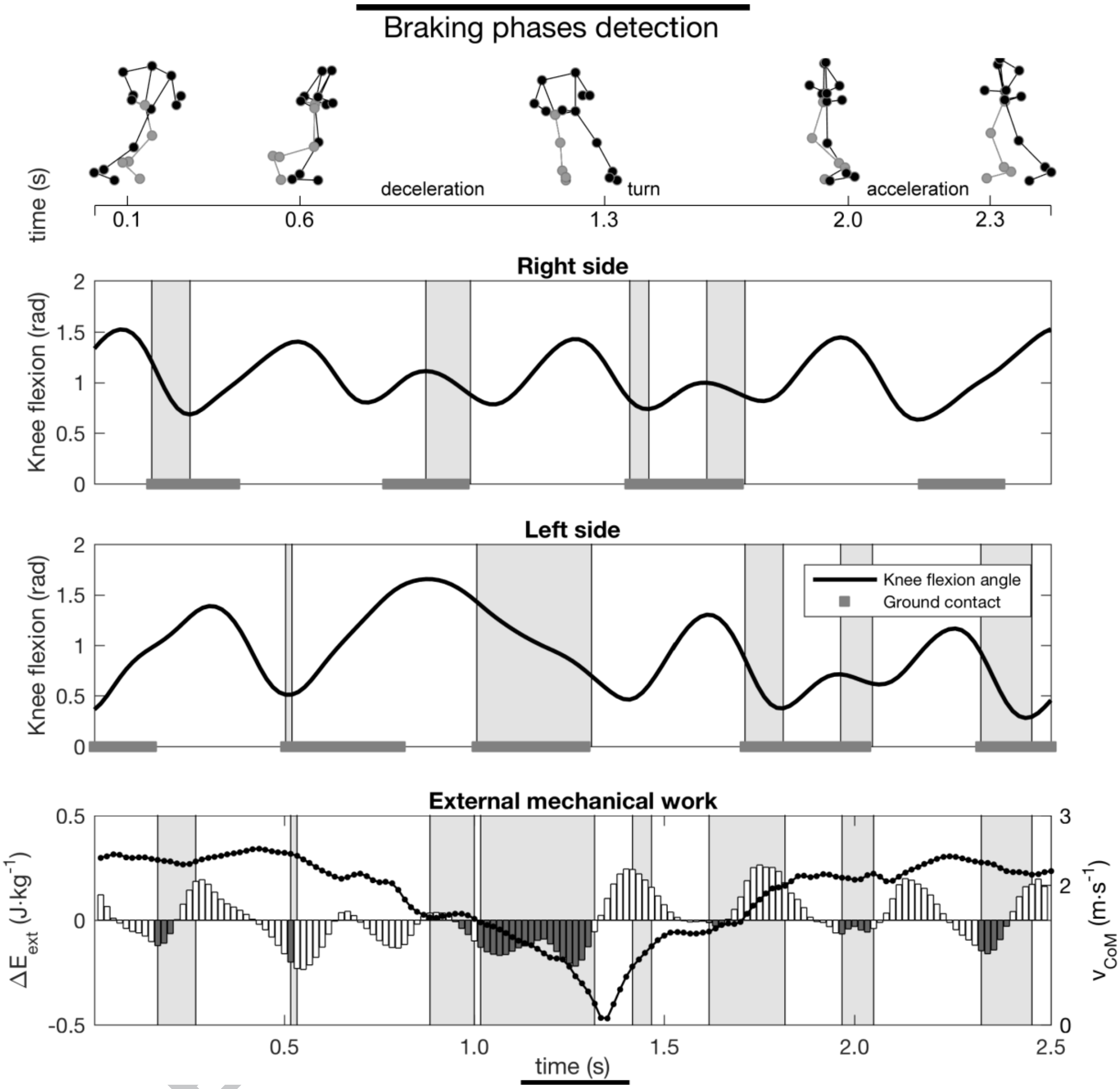
Figure 2: computation of positive and negative work. Plots refer to a single run performed by a single participant (turn is approximately at the center of timeline); top and central panel report knee flexion angle (black line), ground support (thick gray bars) and single-limb braking phases (shaded areas), respectively for the right (gray dots in the stick diagrams) and left leg (black dots). The bottom panel shows external mechanical energy changes (bars lasting 1/60 s), computed as in (Cavagna and Kaneko, 1977). Within braking phases (shaded areas), considered negative work contribution was represented as black bars; the dotted line is the center of mass (CoM) absolute horizontal speed.

Figure 3: measured energy cost vs. Centre of Mass speed (C_{meas} vs. v_{CoM}). The linear regression line is also reported ($r=0.63$, $p<0.001$).

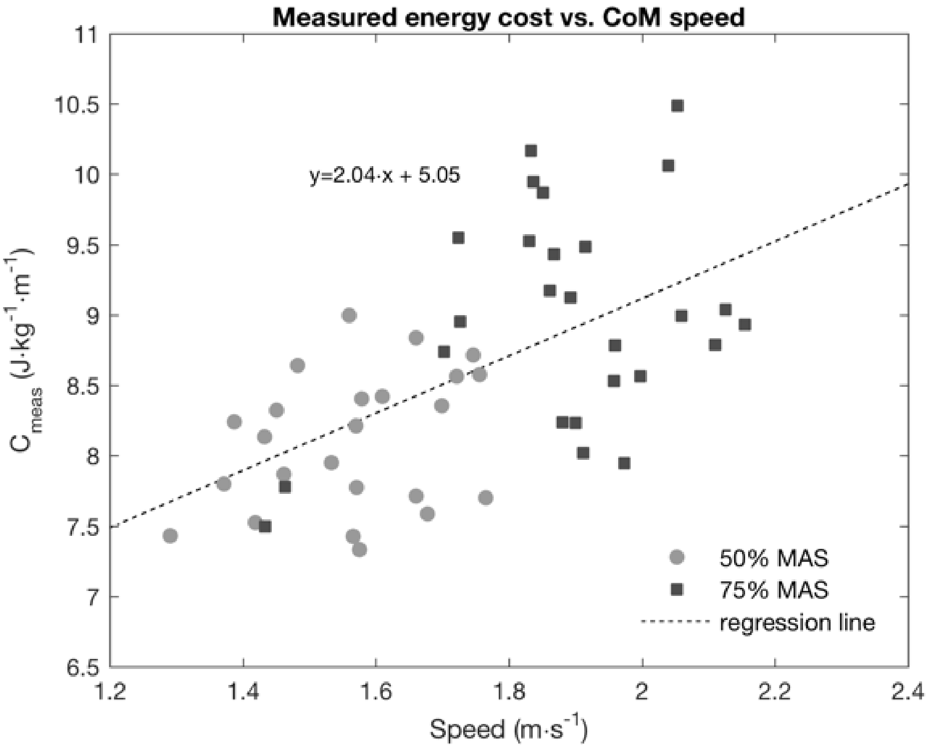
Figure 4: Bland-Altman plot comparing the measured and estimated energy cost of 5-m shuttle running. The difference vs. mean regression line is reported ($r=0.27$, $p=0.064$).

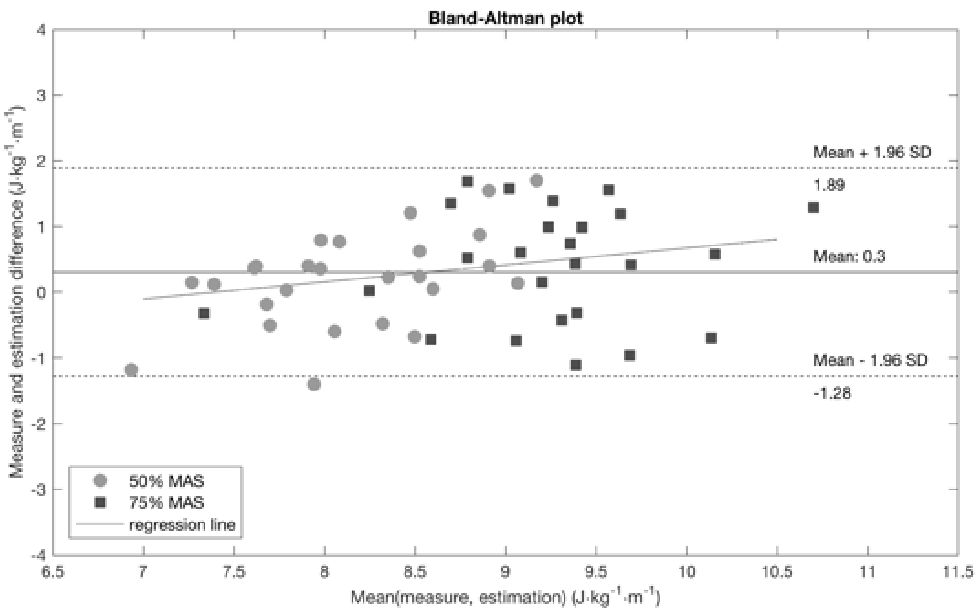


Oxygen uptake, shuttle running test
75% MAS
50% MAS
V'O2 (ml·kg-1·min-1)
time (s)
0
10
20
30
40
50
60
70
200
400
600
800
1000
1200
1400
1600
1800
2000
2200



Braking phases detection
time (s)
deceleration
turn
acceleration
0.1
0.6
1.3
2.0
2.3
Right side
Knee flexion (rad)
Left side
Knee flexion angle
Ground contact
External mechanical work
ΔE_ext (J·kg⁻¹)
v_CoM (m·s⁻¹)
time (s)


Measured energy cost vs. CoM speed
y=2.04·x + 5.05
C_meas (J·kg^-1·m^-1)
Speed (m·s^-1)
50% MAS
75% MAS
regression line


Bland-Altman plot
Mean + 1.96 SD
1.89
Mean: 0.3
Mean - 1.96 SD
-1.28
Measure and estimation difference (J·kg^-1·m^-1)
Mean(measure, estimation) (J·kg^-1·m^-1)
50% MAS
75% MAS
regression line