A KINEMATICALLY BASED ALGORITHM TO ESTIMATE THE ENERGY COST OF VARIABLE-SPEED SHUTTLE RUNNING

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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. The aim of this study is to establish a kinematic-based algorithm to determine the energy cost of running at variable speed with frequent 180° CoDs. Kinematic and metabolic data were simultaneously collected during 5-minutes 5+5 m shuttle run tests. Mechanical work computation was split into positive (eccentric) and negative (concentric) contributions. When compared to the actual energy cost, the estimation algorithm returned an error of 5%. This model constitutes the theoretical basis to extend the model from the laboratory to the field, obtaining an accurate measure of the workload of training and matches.

KEY WORDS: metabolic cost, power, changes of direction, eccentric work.

INTRODUCTION: Turns, or 180° Changes of Direction (CoDs), are essential locomotor patterns in team sports. The acceleration-deceleration dynamics of CoDs require eccentric muscular efforts and high levels of metabolic and mechanical load. A complete understanding of the energy demands of CoDs is necessary to assess the actual energy requirements of exercise, impacting upon injury prevention strategies, training plans, nutrition, and in turn the health of the athletes. With the growth of wearable technology, developing appropriate algorithms for non-steady state running is an important and challenging task. Therefore, the aim of the present study is to establish a kinematic-based algorithm to determine the energy cost of running at variable speed with frequent 180° turns.
Methods of energy cost estimation for sprint running were introduced assuming forward acceleration and deceleration as primary drivers of energy cost. However, when applied to running with consecutive CoDs (shuttle run), they underestimated the actual load by ~15% (Buglione & Di Prampero, 2013). Recently, Zamparo et al. (2016) computed mechanical work in 5-m shuttle run. It was the first attempt to compare metabolic cost and its estimation obtained with a motion capture system, although kinematic and metabolic data were recorded separately. Thus, an additional effort is required to accurately estimate the energy cost of CoDs. We hypothesize that if the proposed algorithm succeeds in estimating the energy cost of many consecutive CoDs, it would be the first step to account for the non-cyclic turns typical of competitions and training. That will be the theoretical basis for its application to wearable technology to be used in sports like soccer, basketball or football.

METHODS: Sixteen physically active male Sports Science students (22.4±3.2 years, BMI 22.9±1.8 kg/m^2) participated in two sessions on separate days: (a) maximum oxygen uptake ($\dot{V}O_{2max}$) and Maximal Aerobic Speed (MAS) were obtained with an incremental discontinuous square wave test; (b) shuttle run test: after baseline measurement, subjects completed a 5-min trial of 5-m shuttle running. To simulate the intermittent activity profile of competition, participants alternated two shuttles (2× 5+5 m) at an average horizontal speed of 50% MAS and two at 75% MAS. An acoustic device helped subjects to keep the proper running speed. Subjects were trained to change the pivoting limb (sidestep cut) at each turn to avoid overloading. In sessions (a) and (b), $\dot{V}O_2$ was measured with a portable metabolimeter (K4, Cosmed, IT). Blood lactate concentration $[La]_b$ was determined. Metabolic cost of exercise (C_{meas}) was obtained from the aerobic, anaerobic alactic and anaerobic lactic energy expenditure, as in Buglione & di Prampero (2013). In session (b), the

3D positions of 17 reflective body markers were recorded with an optoelectronic motion capture system (BTS, IT) at 60 Hz. Raw data were filtered at 15 Hz. Joint angle and CoM kinematics were computed as in Mapelli et al. (2014); CoM external mechanical energy (E_{ext}) was obtained from the potential and kinetic energy components (Willems et al., 1995).
The proposed algorithm assumed that: (i) 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); (ii) positive/negative muscular efficiency is η^{+}=.25 and η^{-}=1.20, respectively (Heglund & Cavagna, 1985); (iii) in running, a large fraction of negative work is done at the knee (Purkiss & Robertson, 2003). The algorithm detects "braking phases", time windows where muscles globally perform mostly negative work. Braking phases (Figure 1) *B(t)* were located at time instants (t) corresponding to knee flexion (negative angular velocity) and ground contacts. The estimated energy cost (C_{est}) was the sum of decrements of E_{ext} (ΔE^{-}_{ext}) during braking phases (*B*), and increments of E_{ext} (ΔE^{+}_{ext}), elsewhere ($\overline{B}$), divided by the related η and by the total CoM horizontal path (d_{CoM}): $C_{est} = \left(\frac{\sum \Delta E^{+}_{ext}|_{\overline{B}}}{\eta^{+}} + \frac{\sum \Delta E^{-}_{ext}|_{B}}{\eta^{-}}\right)/d_{CoM}$. Metabolic power ($\dot{E}_{est}$) was C_{est} multiplied by the average running speed (v_{mean}); v_{mean} was computed dividing d_{CoM} by the exercise time.
Results were compared with the energy cost obtained from the linear regression model proposed by Zamparo et al., (2015): C_z=11.94 v - 12.82 (C_z: energy cost, v: running speed).
Differences between measured and estimation methods were presented as of root mean square (RMSE) and percentage errors, and assessed through a 1-way ANOVA; Tukey post-hoc tests were used to identify significant differences. Significance level was set at α = 5%.

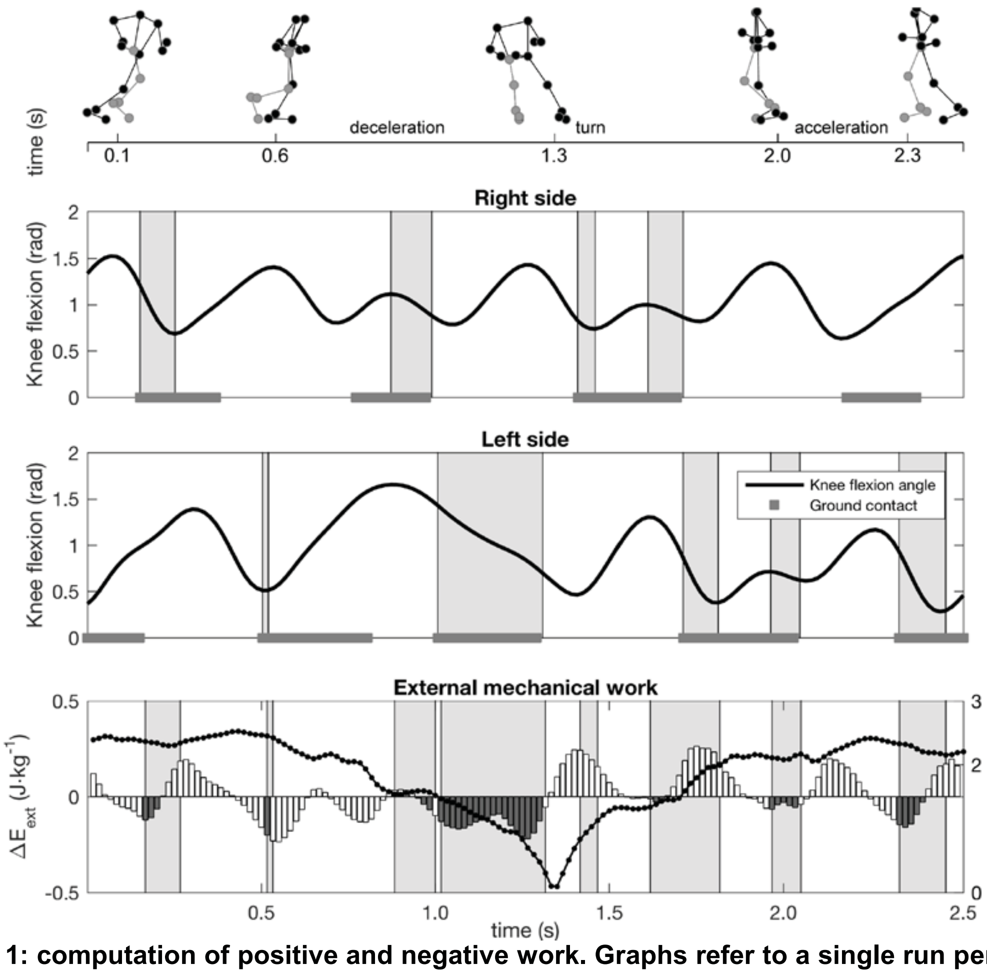

Figure 1: computation of positive and negative work. Graphs refer to a single run performed by a single participant (turn at 1.3 s); upper and central panel report knee flexion angle (right and left), ground support and single-limb braking phases (shaded areas), for the right (gray in the stick diagram) and left leg (black). Bottom panel shows external mechanical energy changes

(bars). Within braking phases, negative work contribution is represented as black bars; the dotted line is the centre of mass (CoM) absolute horizontal speed.

Table 1
Physiological and exercise-related data collected in the shuttle run test.

Variable	Unit	M	SD	Range	
v_{mean}	m s^{-1}	1.84	0.04	1.80	1.92
CoDs/min	min^{-1}	29.5	0.3	28.9	29.9
$\dot{V}O_2$	ml kg^{-1} min^{-1}	44.9	5.3	37.3	57.9
$\%\dot{V}O_{2,max}$	-	82.2	8.2	65.5	94.2
HR	bpm	183.5	8.8	166.6	197.6
$[La]_b$	mM	8.32	3.13	2.90	13.30
$\dot{E}_{meas}$	W kg^{-1}	15.92	1.81	13.00	20.18

RESULTS: $\dot{V}O_{2,max}$ was 55.0±7.2 ml kg^{-1} min^{-1}, and MAS 4.19±0.27 m s^{-1}. Nominal running speeds during the test were between 2 and 3 m s^{-1}, while actual average speed v_{mean} was lower (1.8 m s^{-1}), since CoM travels less than 5+5 m at each shuttle (Table 1). Energy cost of shuttle running ranged from 8.98 to 9.77 J kg^{-1} m^{-1} (Table 2). There were significant differences between measure and estimates (1-way ANOVA, $p<0.05$), in particular C_z was higher than C_{meas} and C_{est}. C_{meas} was not significantly different from C_{meas}, with an estimation error of 5%.

DISCUSSION: The energy expenditure during a *single* shuttle run cannot be easily measured, since accelerations and decelerations solicit the anaerobic metabolism and prevent the attainment of steady state (Dellal et al., 2010; di Prampero, Botter, & Osgnach, 2014). However, after *many* changes of direction a "macroscopically steady" state condition was reached in cardiorespiratory and metabolic parameters, even if the running speed changed every 10-20 s during the test. C_{meas} was comparable with that reported in literature at corresponding speed (Zamparo et al., 2015). Indirect approaches based on 2D CoM kinematics (Buglione & Di Prampero, 2013), underestimated the actual load in shuttle runs shorter than 20 m and shuttle speeds lower than 3.3 m s^{-1} (Stevens et al., 2015; Zamparo et al., 2015).
The equation yielding C_z overestimated C_{meas} ($p<0.01$, Zamparo et al., 2015), but it was obtained with a different exercise protocol (intermittent shuttle and rest periods), where subjects reached higher speeds (3.5 vs ~2 m s^{-1}). The duration of our trials was designed to get a steady state condition and necessarily limited the speed sustainable for the entire test. Although 5-min of continuous shuttle run seldom occurs in real contexts, measured exercise intensity matched the activity profiles of team sports (70-80% of $\dot{V}O_{2,max}$, Spencer et al., 2005).
The proposed algorithm approximated C_{meas} with an error of 5% and improved the existing techniques based just on CoM kinematics, integrating data about ground contacts and knee joint angular kinematics. This allowed distinguishing propulsive from braking phases. Excluding positive work from braking phases, we took the stiffness of muscles and tendons into account: these structures act as temporary stores of mechanical energy, which is absorbed in eccentric and released in concentric conditions. A substantial novelty introduced in this study is the simultaneous recording of kinematic and metabolic data. Then, proposing a realistic biomechanical model instead of a linear regression equation enables to detect the metabolic contribution of various movements like jumps or brakes.
Many physiological factors may lead to estimation errors: fitness level, structural/technical differences, internal energy and energy transfers between limbs and more importantly the efficiency of the conversion from mechanical to metabolic energy. We used recognised average values (as in Zamparo et al., 2016), but each individual has a unique set of coefficients, depending also on speed and exercise conditions (Minetti et al., 2002). Future developments might include individualized characterization of muscular efficiency and

internal work computation. However, the model as it is, has the advantage of a relative simplicity: requiring the computation of just CoM and knee kinematic, its adaptation to portable devices can be planned with a reduced set of wearable units.
Lastly, even if tests on wider velocity/distance spans are required to draw general conclusions, the experiment was purposely designed around the 5-m distance to test the algorithm on a high number of CoDs. Outside of braking/acceleration phases, the algorithm works like previous published methods (Willems et al., 1995; Zamparo et al., 2015).

Table 2
Performance of the energy cost estimation method (units: J kg^{-1} m^{-1}).

Variable	M	SD	RMSE	% Mean error (SD)	
C_{meas}	9.13	0.62	-	-	-
C_{est}	9.28	0.32	0.52	5.0	(3.7)
C_z [a, b]	10.48	0.93	1.45	14.8	(5.8)

1-way ANOVA, p=0.004. Post-hoc: [a] significantly different from C_{meas}, p<0.01;
[b] significantly different from C_{est}, p<0.05.

CONCLUSION: An algorithm to estimate the energetic requirements of running with 180° CoDs based on kinematic data was introduced. The model offers a conceptual understanding of the energetics of turns and provides an accurate estimation of the related metabolic cost. The adaptations of the proposed algorithm to a set of inertial units will extend the model from the laboratory to the field, obtaining a accurate measure of the workload of training and matches.

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