DECELERATION COUNTS: ESTIMATING THE ENERGY COST OF SHUTTLE RUNNING FROM MECHANICAL WORK

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To estimate the energetic requirements of 5-m shuttle running based on kinematic data, we devised a modified version of existing models for the estimation of the energy cost of gait. In our approach, negative/eccentric work during deceleration phases was added to positive/concentric work in propulsive phases. Ten subjects performed two 5-min trials at 50% and 75% of their maximal aerobic speed. The metabolic cost estimated from 3D kinematics was compared to that measured by a portable metabolimeter. The estimation error was 1.2 J/kg/s (7.3%): results encourage to apply this method for the estimation of the workload in sports involving frequent turns and changes of direction.
KEY WORDS: metabolic cost, power, changes of direction, eccentric work.

INTRODUCTION: Quantifying the energy expenditure in team sports can improve training and nutrition planning (Stevens et al., 2014). A relevant contribution to the physiological demands is represented by turns, or 180° changes of direction (Hatamoto et al., 2014). Turns are running actions in which athletes sharply decelerate and accelerate, implying eccentric muscular efforts and increasing the energy cost relative to linear running (Dellal et al., 2010).
The problem of estimating the mechanical work of locomotion has been extensively investigated for walking and running, and the relationship between mechanical work and metabolic energy expenditure has been addressed (Cavagna, Thys, & Zamboni, 1976; Willems, Cavagna, Heglund, Umana, & Chelmsford, 1995). However, the feasibility of methods proposed to study linear gait is not clear in the context of changes of direction. Methods of energy cost estimation during shuttle running based on 2D centre of mass (CoM) kinematics underestimated the actual load (Buglione & di Prampero, 2013).
Thus, additional work has to be done to produce a more accurate estimation of the energy cost of shuttle running based on 3D kinematic data. In particular, since an energy cost is associated with both positive and negative muscle work, the role of the latter should be considered. The purpose of our work was to establish a method based on kinematic data capable of estimating the energy expenditure of shuttle running.

METHODS: Ten physically active male subjects (24.3±3.7 years, BMI 23.9±1.8 kg/m^2) attended two sessions on separate days: 1) maximum oxygen uptake ($\dot{V}O_{2max}$) and maximal aerobic speed (MAS) were obtained with an incremental discontinuous square-wave test; 2) shuttle run test: after baseline measurement, subjects completed two 5-min trials of 5-m shuttle running (sidestep cut) at an average horizontal speed of 50% (v_{low}) and 75% (v_{high}) of their MAS, each followed by a 6 min recovery period. For technical issues, a participant did not complete the second shuttle trial.
In sessions 1 and 2, $\dot{V}O_2$ was measured with a portable metabolimeter (K4b, Cosmed, Rome, IT). Blood lactate concentration was determined with a lactate analyser (LacPro, BST, Berlin, DE) on a sample obtained from the ear lobe after the test. The metabolic cost of shuttle running C_{sh} was obtained from the $\dot{V}O_2$ data by summing the aerobic, anaerobic alactic and anaerobic lactic energy expenditure (Buglione & di Prampero, 2013). After each trial, subjects provided a rating of perceived exertion (RPE) using the 6-20 Borg scale.
In session 2, the instantaneous positions of 17 reflective body markers were recorded at 60 Hz with an optoelectronic motion capture system (BTS, Milano, IT). Raw data were filtered at 15 Hz; CoM and knee joint angular kinematics were computed. CoM mechanical external

energy (E_{ext}) was computed summing the potential and kinetic energy components (Willems et al., 1995). The proposed estimation method assumes that:

1. The body mass is located in the CoM.
2. Even though during running part of the decrease/increase of total energy is caused by tendon stretch and recoil (Purkiss & 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 muscular efficiency of positive and negative work is supposed to be 25% and 120%, respectively (Cavagna et al., 1976).
4. During running, a large fraction of negative work is done at the knee, since muscles at this joint are working as stabilizers and shock absorbers (Purkiss & Robertson, 2003).

We located the phases of greater negative work ("braking" phases) when at least one foot is touching the ground (detected through vertical position and speed thresholds) and the knee is flexing (Figure 1). The overall metabolic power estimated from kinematic approach was obtained as the sum of decrements of E_{ext} in the braking phases, and increments of E_{ext} elsewhere, multiplied by the related efficiency and divided by the exercise time.
Coefficient of determination (R^2), root-mean-square error (RMSE) and Bland-Altman plot were used to compare the measured and estimated values of metabolic power.

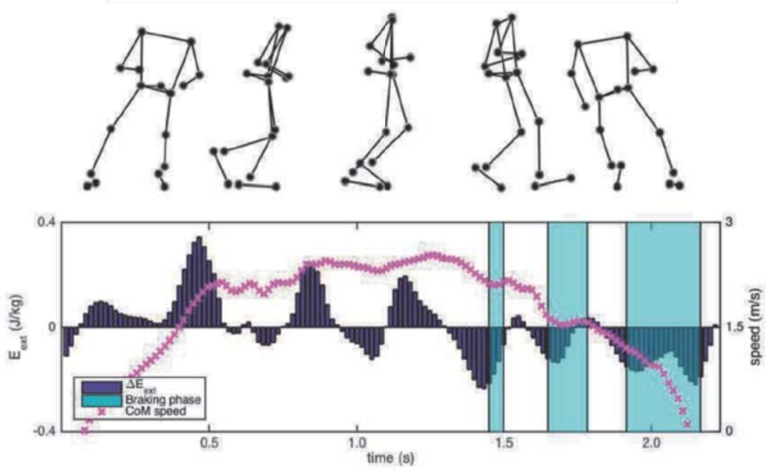

Figure 1: detection of braking phases (shaded areas): blue bars are positive and negative external energy changes in a single change of direction; crosses reports CoM speed,

RESULTS: Mean MAS was 14.2±1.6 km/h. Nominal shuttle speed, measured power and RPE in the two test conditions were: v_{low}=6.8±0.9 km/h, C_{sh}=10.9±1.7 J/kg/s, RPE=9±1; v_{high}=10.4±1.3 km/h, C_{sh} =10.9±1.7 J/kg/s, RPE: 14±2. The measured energy cost per unit distance varied from 6.8 to 9.8 J/kg/m. The fraction of calculated negative (braking phases) vs. positive work during exercise was 7.0±5.1%. After the removal of a single outlier (measured power ≥ mean + 1.96 SD), the estimation reported a RMSE of 1.2 J/kg/s (R^2=0.88, p<0.001, Figure 2), with an average error of 7.3%.

DISCUSSION: Despite changes of direction are among the essential locomotor patterns in ball sports (Hatamoto et al., 2014), their very nature prevents the attainment of a steady state, making it difficult to estimate the corresponding biomechanical energy expenditure (di Prampero, Botter, & Osgnach, 2014).

The continuous accelerations and decelerations relatively break the linear kinetics of the VO_2 and solicit the anaerobic metabolism at a higher level (Dellal et al., 2010). This intrinsic "non-steady-state" condition was overcome by computing the energy expenditure over a 5-min window of continuous ("macroscopically steady") shuttle running.

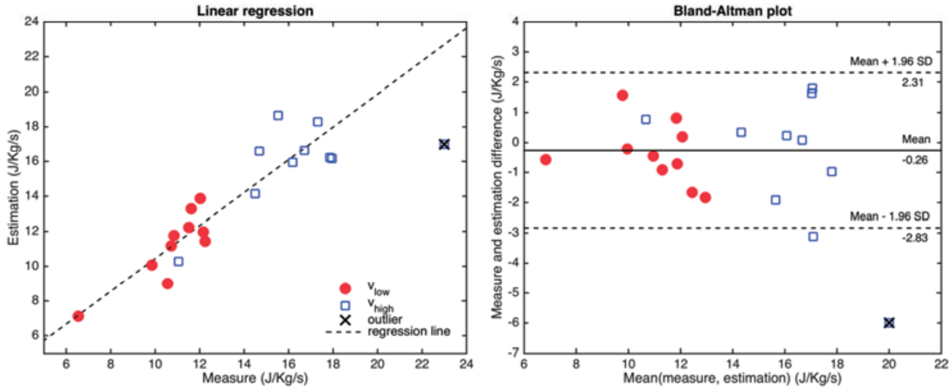

Figure 2: correlation (R^2=0.88, left) and Bland-Altman plots (right) comparing the measured and estimated values of metabolic power.

The measured energy cost was comparable with that reported by Zamparo et al. (2014) and slightly higher than that reported by Stevens et al. (2014) for 10-m shuttle run. That agrees with the observation by which the energy cost of a change of direction significantly increases with running velocity and decreases with shuttle distance (Hatamoto et al., 2014).

Methods for the estimation of the energy cost of locomotion were historically developed based on pendulum (walk) and spring (run) analogies (Willems et al., 1995). However, the classic approach of just integrating the positive increments of E_{ext} appeared not applicable to the turn technique. In this kind of exercise, the energetic cost is incomplete without consideration of negative work, and only part of positive work is related to metabolic work (Van Ingen Schenau, Bobbert, & de Haan, 1997). In particular, even though some positive and negative work can be performed passively by elastic elements rather than by active contractile elements, it was also proven that apparent leg elasticity can be achieved with at least some muscle work (Kuo, 2007).

Conversely, our approach considered the contribution of negative work in braking phases, and the contribution of positive work in propulsive phases. Although during double support, (the last sidestep of turns) the legs perform simultaneously positive and negative work with substantial metabolic work (Kuo, 2007), we regarded at "braking phases" as windows of "mostly negative" work. The braking phases occurred mainly just before the turn, as expected. Moreover, this approach considers muscles and tendons stiffness in linear running: these structures act as temporary stores of mechanical energy, which are absorbed in eccentric and then released in concentric conditions (Asmussen & Bonde-Petersen, 1974). The obtained percentage of detected negative work, on average below 10% of positive work, appeared coherent with this principle.

Our estimation returned an error lower than 10%. 2D kinematic approaches based on sprint running models (di Prampero et al., 2014) underestimated by 15% the actual cost of shuttle running and are sensitive to the tracking technology and data filtering (Stevens et al., 2014).

However, some limitations of our method have to be pointed out. First, some negative work might have been performed by the shoes, plantar ligaments, and also in the damped motion of fat, viscera and muscles: this dissipation is difficult to quantify theoretically and empirically (Kuo, 2007), and it was not taken into account. Second, many physiological factors may lead to variability in mechanical work: fitness level, baseline subtractions, technical differences, and more importantly the efficiency of the conversion from mechanical to metabolic energy. In fact, in our model we assumed positive and negative work efficiencies as constant, but each individual has a unique set of coefficients, which are also a function of speed. Lastly, the contribution of internal energy, and energy transfers between limbs, was not considered.

Then, though the proposed method offers a conceptual understanding of the energetics of turns, it does not claim to provide a detailed picture of the complex mechanisms involved.

For these reasons, further investigations are required to draw conclusions about the effectiveness of the proposed technique, to test the influence of wider velocity/distance spans and participants' fitness levels.

CONCLUSION: To estimate the energetic requirements of 5-m shuttle running based on kinematic data, we introduced an algorithm accounting for both positive and negative mechanical work, the latter considered during deceleration (eccentric work) phases.
Since it is able to detect the energy requirements of turns, but potentially also jumps and other team sports techniques, the proposed methods could be the basis to provide an accurate estimation of the energy requirements of matches and training, impacting upon prevention strategies and ultimately the health of the players.

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