Human Movement Science 66 (2019) 487–496

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Mechanical work in shuttle running as a function of speed and distance: Implications for power and efficiency

Paola Zamparo[a,*], Gaspare Pavei[b], Andrea Monte[a], Francesca Nardello[a], Takuya Otsu[c], Naoki Numazu[c], Norihisa Fujii[c], Alberto E. Minetti[b]

[a] Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Verona, Italy
[b] Department of Pathophysiology and Transplantation, University of Milano, Milano, Italy
[c] Faculty of Health and Sport Sciences, University of Tsukuba, Tsukuba, Japan

ARTICLE INFO

Keywords:
Human locomotion
Mechanical work
Mechanical efficiency
Shuttle runs

ABSTRACT

Biomechanics (and energetics) of human locomotion are generally studied at constant, linear, speed whereas less is known about running mechanics when velocity changes (because of accelerations, decelerations or changes of direction). The aim of this study was to calculate mechanical work and power and to estimate mechanical efficiency in shuttle runs (as an example of non-steady locomotion) executed at different speeds and over different distances. A motion capture system was utilised to record the movements of the body segments while 20 athletes performed shuttle runs (with a 180° change of direction) at three paces (slow, moderate and maximal) and over four distances (5, 10, 15 and 20 m). Based on these data the internal, external and total work of shuttle running were calculated as well as mechanical power; mechanical efficiency was then estimated based on values of energy cost reported in the literature. Total mechanical work was larger the faster the velocity and the shorter the distance covered (range: 2.3–3.7 J m^{-1} kg^{-1}) whereas mechanical efficiency showed an opposite trend (range: 0.20–0.50). At maximal speed, over all distances, braking/negative power (about 21 W kg^{-1}) was twice the positive power. Present results highlight that running humans can exert a larger negative than positive power, in agreement with the fundamental proprieties of skeletal muscles in vivo. A greater relative importance of the constant speed phase, associated to a better exploitation of the elastic energy saving mechanism, is likely responsible of the higher efficiency at the longer shuttle distances.

1. Introduction

The majority of the studies on human or animal locomotion are conducted at steady/constant speed (e.g. treadmill locomotion or ground locomotion along a linear path) even if, in real life, human's and animal's gaits very often occur at variable/non-steady speed (Minetti, Ardigò, Capodaglio, & Saibene, 2001; Minetti, Gaudino, Seminati, Giacometti, & Roi, 2013; Wilson, Griffiths et al., 2013; Wilson et al., 2015). As an example, during hunting, a predator combines speed, agility and endurance to maximize capture success; during these manoeuvres accelerations and deceleration phases, as well as turns and changes of direction are performed by both pray and predator in a race for survival (e.g. Wilson, Griffiths et al., 2013; Wilson et al., 2015).

* Corresponding author at: Department of Neurosciences, Biomedicine and Movement Sciences, University of Verona, Via Felice Casorati, 43, 37131 Verona, Italy.
E-mail address: paola.zamparo@univr.it (P. Zamparo).

https://doi.org/10.1016/j.humov.2019.06.005
Received 6 February 2019; Received in revised form 7 June 2019; Accepted 8 June 2019
Available online 13 June 2019

Besides a general interest in describing the fundamental aspects of non-steady legged locomotion in humans, the interest in these matters is driven by the need to understand the mechanics and energetics of activities typical of team sports where human's movement resemble indeed those of prey and predator, e.g. in the attempt to catch and keep possession of a ball (or to avoid that someone else gets hold of it). Indeed, in football, soccer or rugby large accelerations and decelerations can be observed, as well as turns and sudden changes of directions (e.g. di Prampero, Botter, & Osgniach, 2015; Osgniach, Poser, Bernardini, Rinaldo, & di Prampero, 2010; Taylor, Wright, Dischiavi, Towsen, & Marmon, 2017).

Shuttle runs (SR) are a good model of unsteady locomotion: they are characterized by an acceleration phase (where mainly positive power is exerted), a deceleration phase (where mainly negative power is exerted) and a change of direction (CoD: a 180° turn) and can be performed at different speeds and over different distances.

The energetics of shuttle running has been only recently investigated (e.g. Bucheit, Haydar, Hader, Ufland, & Ahmaidi, 2011; Buglione & di Prampero, 2013; Stevens et al., 2015; Zadro, Sepulcri, Lazzer, Fregolent, & Zamparo, 2011; Zamparo, Zadro, Lazzer, Beato, & Sepulcri, 2014; Zamparo, Bolomini, Nardello, & Beato, 2015; Zamparo et al., 2016) because the energy expenditure during a single SR does not reach a steady state and thus cannot be easily determined. These studies have shown that the energy cost (*C*, $J\,kg^{-1}\,m^{-1}$, the energy expended per unit distance) in SR increases with shuttle velocity and decreases with shuttle distance (e.g. Buglione & di Prampero, 2013; Zamparo et al., 2014) and is far larger than the values of *C* generally reported during linear, constant speed running, a condition in which *C* is rather unaffected by the speed (e.g. Cavagna & Kaneko, 1977; di Prampero et al., 2015; Saibene & Minetti, 2003).

Shuttle running thus implies a significant increase in energy expenditure compared to running at constant-linear speed mainly because of the accelerations and decelerations phases but also because of the changes of direction; turns are indeed associated with additional energy expenditure relative to straight line walking or running (McNarry, Wilson, Holton, Griffiths, & Mackintosh, 2017; Minetti, Cazzola, Seminati, Giacometti, & Roi, 2011; Zamparo et al., 2014; Wilson, Speakman et al., 2013).

The mechanics of SR has received less attention so far. Only a recent study (Zamparo et al., 2016) reports data of mechanical work (W_{tot}, $J\,kg^{-1}\,m^{-1}$) in SR and only over a distance of 5 + 5 m. The results of this study indicate that W_{ext} (the work to raise and accelerate the body center of mass -BCoM- within the environment) in SR is about twice that of linear, constant speed running and that W_{int} (the work to accelerate and decelerate the limbs in respect to the BCoM) accounts for 50% of total mechanical work when the shuttle velocity is high. In that study the energy cost of SR was also determined with the aim to calculate mechanical efficiency in SR ($eff = W_{tot}/C$); efficiency was found to be much lower than that reported for linear running (e.g. as reported by Cavagna & Kaneko, 1977) probably due to: i) lower elastic energy reutilization given the short distance covered, ii) more muscle co-activation required to stabilize the body (during turns) and iii) muscle fascicles probably working at less favourable lengths and velocities in SR than during constant linear running.

The aims of this study were: i) to obtain a comprehensive description of SR mechanics as a function of shuttle distance and velocity (mechanical data are reported only for a short shuttle distance, 5 + 5 m); ii) to investigate the implications that SR mechanics have on mechanical efficiency in non-steady speed conditions (available data suggest a lower elastic energy reutilization compared to linear running). In particular, we hypothesized that: i) total mechanical work per unit distance would increase as a function of velocity for each shuttle distance but, at any given velocity, it would decrease with the shuttle distance (as is the case for the energy cost of shuttle running); ii) mechanical efficiency would be larger the longer the distance covered (e.g. the smaller the time spent in the acceleration/deceleration phases).

A further purpose of this study was to compare positive and negative power production during the acceleration and deceleration phases of shuttle runs covered at maximal speed since no data in the literature are reported regarding the power that can be expressed by humans when decelerating (whereas the acceleration phase is quite extensively investigated in the literature, e.g. Nagahara, Mizutani, Matsuo, Kanehisa, & Fukunaga, 2018; Slawinski et al., 2017).

2. Methods

2.1. Subjects

Experiments took place at the Biomechanics Facility of the University of Tsukuba (Japan). Twenty healthy Japanese (16 males and 4 females) were recruited for this study (22.3 ± 1.17 years of age, 67.0 ± 11.8 kg of body mass, 1.73 ± 0.07 m of stature); they were practicing different sports activities (athletics, tennis, judo and team sports such as basketball, soccer, volleyball and handball) 2.1 ± 0.9 h per day and 4.6 ± 1.6 times per week, on the average. Of these athletes, 13 declared to be familiar with the CoD. Informed consent was obtained from each participant in accordance with the approval of the Institutional Review Board of the Department of Neurosciences, Biomedicine and Movement Sciences of the University of Verona (Italy) (Agreement No. 5818, 2017). The study was in agreement with the Declaration of Helsinki for the study on human subjects.

2.2. Technical setup and instrumentation

A motion capture system (Vicon MX, Oxford Metrics, UK) was utilised to record the 3D body motion; 35 cameras were utilised (13 T20s; 12 T20; 2 T10s; 8 T10) to cover the entire volume; kinematic data were acquired at a sampling rate of 100 Hz (see Fig. A.1 in Supporting Information). The coordinates (x: antero-posterior; y: medio-lateral, z: vertical) of 18 reflective markers located on the main joint centres were recorded so that the body was considered composed by 12 segments (trunk: greater trochanter/gleno-homeral axis; head: gleno-homeral axis/vertex; thigh: greater trochanter/femoral condyle; shank: femoral condyle/lateral malleolus;

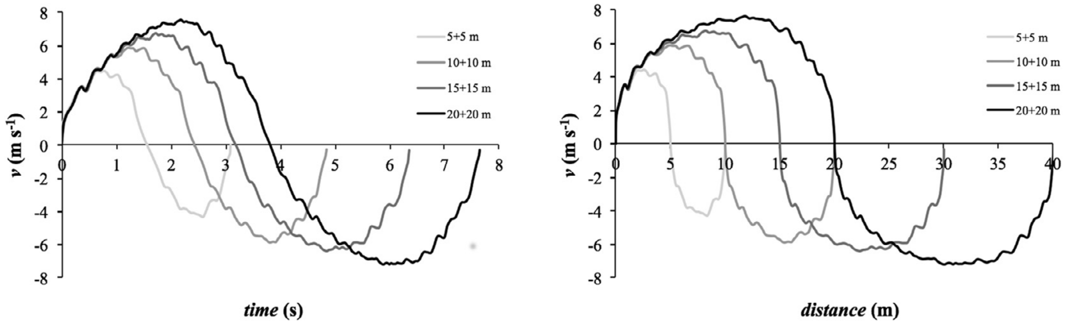

Fig. 1. BCoM horizontal velocity (m s^{-1}) as a function of shuttle time (s, left panel) or distance (m, right panel) during shuttle runs over different distances: 5 + 5 m (light grey line); 10 + 10 m (grey line); 15 + 15 m (dark grey line) and 20 + 20 m (black line).

foot: calcaneous/tip toe; upper arm: gleno-homeral axis/elbow axis; forearm: elbow axis/ulnar styloid). The mass of each segment and the radius of gyration were determined according to Ae, Tang, and Yoki (1992) inertial parameters in order to calculate the 3D trajectory of the body center of mass (BCoM).

2.3. Experimental design and procedure

The design of the study is non-experimental, descriptive and correlational.

All participants were requested to perform shuttle runs over a distance of 5 + 5 m, 10 + 10 m, 15 + 15 m and 20 + 20 m (with a 180° change of direction, CoD) at different self-selected paces (slow, moderate and maximal), during which kinematic data were recorded. Each subject performed 2 trials in each condition. An initial warm-up (i.e. running, specific gaits and CoD) was proposed to each athlete to familiarise with the procedures. The subjects used their own sport shoes and the pavement floor of the indoor Gym was in PVC (see Fig. A.1 in Supporting Information).

Subjects were requested to position the right foot over the starting line and to touch, with their right hand, a 30 cm tall cone positioned at their side; they were then requested to reach (and touch) a second cone (positioned at a distance of 5, 10, 15 or 20 m) and to change direction a first time; after that they were requested to reach (and touch) the cone positioned at the starting line, to change direction again and then to stop, after one or two steps. No further indications were given so that the subjects freely chose when to stop the acceleration phase and start to decelerate.

The profile of horizontal velocity of the BCoM as a function of time or distance covered (at maximal velocity) is reported in Fig. 1 for a representative subject: this figure shows that each SR is composed by two acceleration and two deceleration phases; negative values of velocity are observed in the second half of the SR because of the change of direction. This figure also shows that, when shuttle distance increases the duration of the acceleration phase also increases so that larger values of velocity can be attained before the deceleration phase starts. This figure also indicates that the acceleration phase lasts more than the deceleration phase, over all shuttle distances.

2.4. Data analysis

2.4.1. Mechanical work calculations

Based on BCoM position data the time course of potential (E_P) and kinetic (E_K) energies was computed in order to obtain total mechanical energy ($E_T = E_P + E_{KX} + E_{KY} + E_{KZ}$). The profiles of E_T, E_P and E_K (in the x, y and z axes) as a function of the shuttle distance (at maximal velocity) are reported for a representative subject in Fig. 2. This figure shows that E_T increases in the acceleration phase and decreases in the deceleration phase over all distances and that E_{KX} contributes most to E_T, followed by E_P, whereas the contribution of E_{KY} and E_{KZ} is negligible over all distances.

Positive external work (W^+_{ext}, J kg^{-1} m^{-1}) was calculated based on the summation of all increases in E_T time course (Cavagna & Kaneko, 1977); conversely, the summation of all decreases in E_T time course gives the negative external work (W^-_{ext}, J kg^{-1} m^{-1}) (Minetti, Ardigò, & Saibene, 1993). The work necessary to rotate and accelerate the limbs with respect to BCoM (the positive internal work, W^+_{int}, J kg^{-1} m^{-1}) was calculated according to Cavagna and Kaneko (1977) and Minetti et al. (1993). Finally, total mechanical work (W^+_{tot}, J kg^{-1} m^{-1}) was calculated as the sum of W^+_{int} and W^+_{ext} (as previously proposed for walking and running at constant, linear speed). Data of W^+_{int}, W^+_{ext} and W^+_{tot} are reported in the paper normalized per shuttle distance (e.g. expressed in J kg^{-1} m^{-1}). Data were analysed with a custom written software (LabVIEW 10, National Instrument, USA).

2.4.2. Mechanical efficiency calculations ("apparent" efficiency)

In several studies referring to constant speed-linear walking or running, mechanical efficiency is calculated as $W^+_{tot} \cdot C^{-1}$, where W^+_{tot} is calculated as described above and C is the net energy cost of walking/running (e.g. Cavagna & Kaneko, 1977; Pavei & Minetti, 2016; Saibene & Minetti, 2003; Willems, Cavagna, & Heglund, 1995, Peyré-Tartaruga & Coertjens, 2018). This efficiency is sometimes defined as locomotion efficiency or "apparent" efficiency since it can assume values that exceed those of "pure" muscle

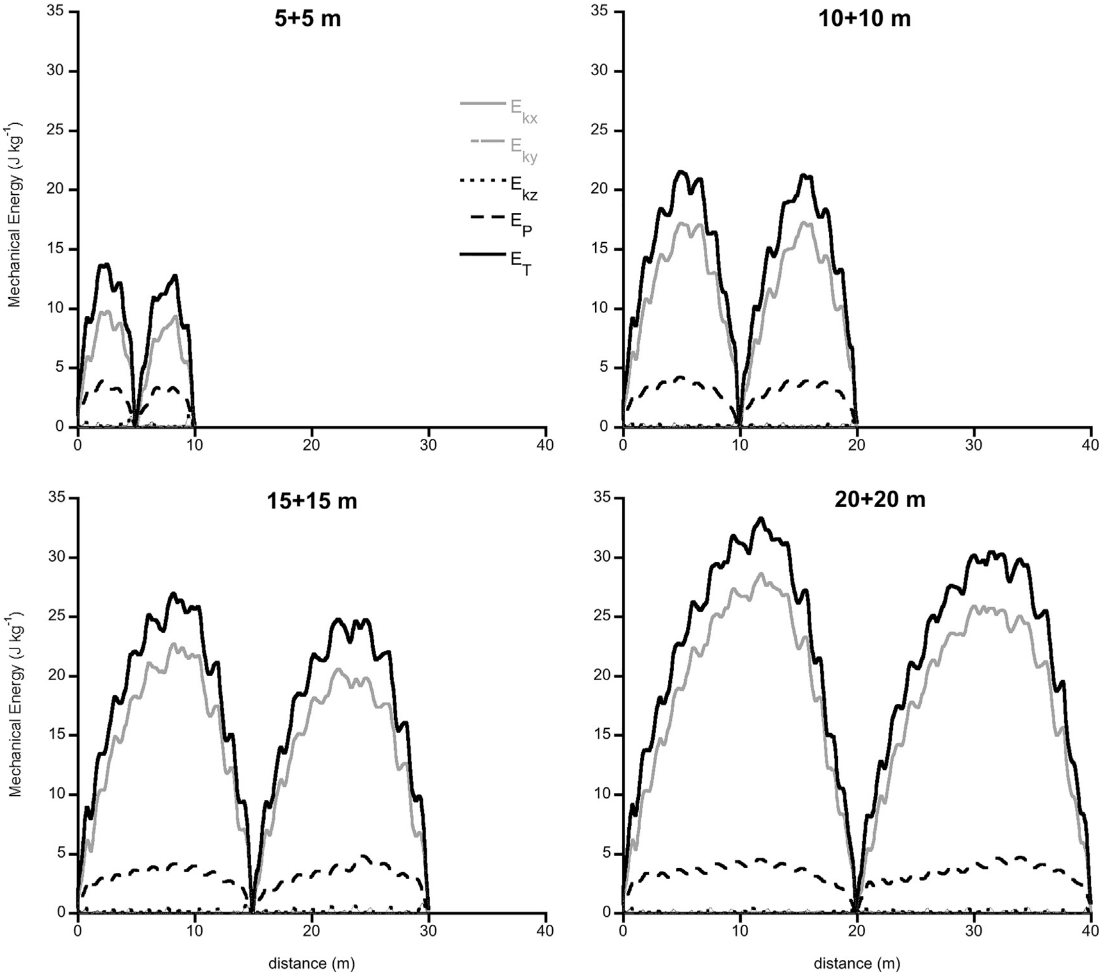

Fig. 2. Time course of BCoM kinetic (E_{kx},: dark grey continuous line; E_{ky}, dark grey dashed line; E_{kz}; black dotted line), potential (E_p, light grey continuous line) and total (E_T, black continuous line) energies (J kg^{-1}) as a function of shuttle distance during 5 + 5 m (top-left panel), 10 + 10 m (top-right panel), 15 + 15 m (bottom-left panel) and 20 + 20 m (bottom-right panel) shuttle runs.

efficiency (e.g. larger than 0.25–0.30). As an example, in constant speed linear running, "apparent" efficiency can be as large as 0.5–0.6 (Cavagna & Kaneko, 1977) and this indicates that mechanical work could result from elastic recoil of muscle tendon-structures, other than muscular work *per se*. In those forms of locomotion where no or little stretch occurs (e.g. cycling and swimming), the work generated by the muscles force almost entirely flows into the mechanical work measured at the whole-body level so that "apparent" efficiency is close to, or lower than, 0.25–0.30.

Thus, mechanical (or "apparent ") efficiency is not a measure/indication of muscle efficiency *per se,* since an increase in its values does not indicate that the muscles work in a more efficient way (as pointed out by Ettema, 2001); this efficiency is, however, calculated in locomotion studies to obtain insight into the mechanisms of conversion of metabolic energy into mechanical work (at the whole-body level) because it can help to understand whether work has be "recycled" via storage and release of elastic energy (e.g. an energy saving mechanism, as suggested by Alexander, 1991).

It goes without saying that the values of mechanical ("apparent") efficiency, for a given metabolic input (e.g. *C*), depend on the methods adopted to define, measure or calculate mechanical work in all its components (internal and external, positive and negative, see Discussion). In this study we adopted the methods described above, to be able to compare our efficiency data with those already reported in the literature for running (e.g. Cavagna & Kaneko, 1977) and shuttle running (Zamparo et al., 2016). In our previous work we reasoned on the differences between SR and constant speed linear running and we concluded that, since in SR braking can be substantial, also negative work (W^-_{tot} in both its components: W^-_{ext} and W^-_{int}) should be taken into account in the computation of efficiency whereas its metabolic counterpart is already included in the measured *C*. In that paper we show that, since negative and positive work ought to be the same ($W^+_{tot} = W^-_{tot}$, as is the case when running on the level), by assuming a constrained ratio between positive and negative work efficiency of 1:5 (compatibly with previously reported data from muscle physiology, e.g. Woledge, Curtin, & Homsher, 1985), efficiency of positive work in SR can be calculated as: $eff^+_{tot} = 6/5\ W^+_{tot} \cdot C^{-1}$. The 6/5 term thus corrects eff^+_{tot} for the presence of negative work (internal and external) (for further details see Zamparo et al., 2016).

In this study, the efficiency in SR was thus estimated/calculated, based on the values of W^+_{tot} (at a given average shuttle velocity, e.g. v_{mean}) and on data of net energy cost of shuttle running (C) at the very same velocity as obtained by applying the C vs. v_{mean} relationships reported in the literature for shuttle runs over the 5 + 5 m distance ($C = -12.82 + 11.94 \cdot v_{mean}$; Zamparo et al., 2015), 10 + 10 m distance ($C = -12.72 + 6.75 \cdot v_{mean}$; Buglione & di Prampero, 2013) and 20 + 20 m distance ($C = -1.83 + 2.34 \cdot v_{mean}$; Buglione & di Prampero, 2013); as discussed in detail in these papers, these values of C are calculated by taking into account the anaerobic (lactic and alactic) contribution. No metabolic data are reported in the literature for the 15 + 15 m distance; hence efficiency was not estimated/calculated in this specific case.

2.4.3. Mechanical power calculations

In shuttle runs over all distances, but only at maximal velocity, average mechanical power (P, W kg^{-1}) was calculated in the deceleration phase preceding the first CoD (negative power, P^-) and in the acceleration phase following it (positive power, P^+) from the ratio $\Delta E_T/\Delta t$, where Δt (s) is the duration of the acceleration or deceleration phases. These calculations were performed in two intervals: i) over the entire acceleration/deceleration phase: ΔE_T (J kg^{-1}) = $E_{Tmax} - E_{T0}$, from v_{max} to $v = 0$ (before the CoD) and from $v = 0$ to v_{max} (after the CoD); ii) by considering a "cut off" in the total energy time course ($\Delta E_T = 5$ J·kg^{-1}) common for all distances ($\Delta E_T = E_{T5} - E_{T0}$, before and after the CoD). In the former case power is calculated over a different number of steps (depending on the shuttle distance) whereas in the latter case the cut off corresponds, with good approximation, to the first/last running step before and after the CoD (over all shuttle distances).

Finally, in shuttle runs over all distances, but only at maximal velocity, the average values of acceleration (*acc*) and deceleration (*dec*) were calculated over the entire acceleration/deceleration phase: from v_{max} to v = 0 (before the CoD) and from $v = 0$ to v_{max} (after the CoD).

2.5. Statistical analysis

Data are reported as averages ± SD. A two way ANOVA was performed to investigate the effects of shuttle distance and of the method employed to calculate power on the values of P^-, P^+ and the P^-/P^+ ratio (at maximal velocity only). A Bonferroni post hoc test was used to determine the possible differences between groups according to speed or distance. A one-way ANOVA was performed to investigate the effects of distance (at maximal velocity only) on the values of *acc, dec* and the *dec/acc* ratio. Statistical analyses were performed with SPSS version 20 (IBM). Statistical significance was set at α-value of < 0.05.

3. Results

The average values of v_{mean} and v_{max}, of W^+_{ext}, W^+_{int} and W^+_{tot} at the three velocities and over the four shuttle distances are reported in Table 1. The individual values of W^+_{ext}, W^+_{int} and W^+_{tot} are reported in Figs. A.2 and A.3 (Supporting Information) as a function of the average shuttle speed for each shuttle distance. In Fig. A.4 (Supporting Information) the partitioning of the total work in its internal and external components is reported, as well as the partitioning of the external work in its "vertical and horizontal" components as a function of shuttle distance and speed.

Fig. 3 reports the average values of total mechanical work (W^+_{tot}, upper panel) and mechanical efficiency (eff^+_{tot}, lower panel) as a function of shuttle distance for each shuttle speed; this figure shows that total mechanical work increases with shuttle speed and decreases with shuttle distance (Fig. 3, upper panel). The increase in W^+_{tot} with speed (for a given distance) is larger than its decrease with distance (for a given speed): W^+_{tot} is about 30% larger at maximal than at slow speed (average over all distances) and about 10% lower at 20 vs. 5 m (average at all speeds). Mechanical efficiency decreases with shuttle speed and increases with shuttle distance (Fig. 3, lower panel). The difference in eff^+_{tot} between 5 and 10 m is larger than the difference in eff^+_{tot} between 10 and 20 m; about 40%

Table 1
Average (± SD) values of shuttle velocity and mechanical work at different paces and over different distances.

distance m	pace	v_{mean} m·s^{-1}	v_{max} m·s^{-1}	$W_{ext}{}^+$ J·kg^{-1}·m^{-1}	$W_{int}{}^+$ J·kg^{-1}·m^{-1}	$W_{tot}{}^+$ J·kg^{-1}·m^{-1}
5 + 5	S	2.02 ± 0.2	2.83 ± 0.3	1.90 ± 0.2	0.64 ± 0.1	2.54 ± 0.2
	M	2.53 ± 0.2	3.52 ± 0.3	1.99 ± 0.2	0.89 ± 0.12	2.88 ± 0.2
	max	3.08 ± 0.3	4.22 ± 0.3	2.28 ± 0.2	1.39 ± 0.26	3.67 ± 0.5
10 + 10	S	2.68 ± 0.3	3.44 ± 0.3	1.73 ± 0.1	0.65 ± 0.07	2.38 ± 0.2
	M	3.32 ± 0.3	4.39 ± 0.4	1.80 ± 0.2	0.88 ± 0.11	2.68 ± 0.2
	max	3.90 ± 0.3	5.45 ± 0.4	2.06 ± 0.1	1.38 ± 0.22	3.45 ± 0.4
15 + 15	S	3.05 ± 0.4	3.90 ± 0.5	1.65 ± 0.1	0.67 ± 0.07	2.32 ± 0.1
	M	3.67 ± 0.3	4.82 ± 0.5	1.67 ± 0.2	0.86 ± 0.12	2.53 ± 0.2
	max	4.44 ± 0.3	6.21 ± 0.5	1.97 ± 0.2	1.41 ± 0.23	3.37 ± 0.4
20 + 20	S	3.25 ± 0.4	4.09 ± 0.5	1.60 ± 0.1	0.68 ± 0.06	2.28 ± 0.1
	M	3.98 ± 0.4	5.10 ± 0.6	1.62 ± 0.1	0.87 ± 0.11	2.49 ± 0.2
	max	4.86 ± 0.4	6.75 ± 0.6	1.88 ± 0.2	1.43 ± 0.21	3.31 ± 0.4

S: slow shuttle velocity; M: moderate shuttle velocity; max: maximal shuttle velocity; v_{mean}: average velocity of the shuttle run; v_{max}: maximal velocity of the shuttle run; W^+_{ext}: positive external mechanical work; W^+_{int}: positive internal mechanical work; W^+_{tot}: positive total mechanical work.

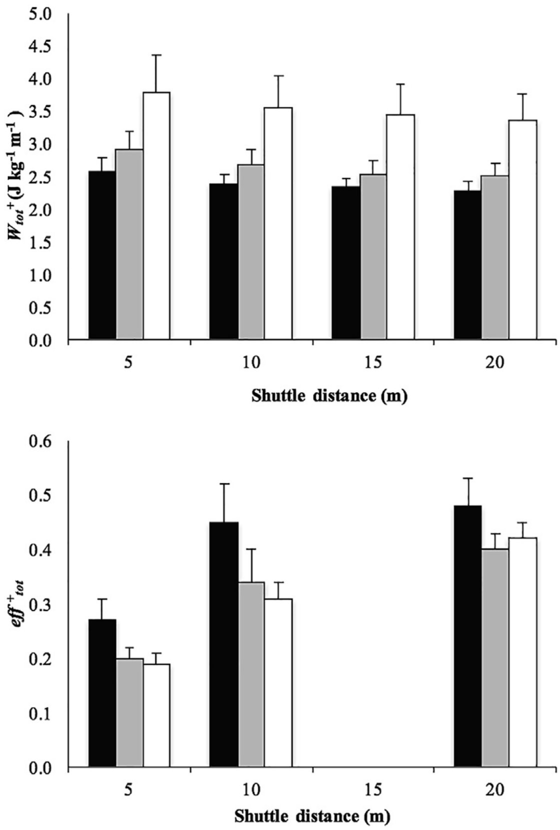

Fig. 3. Total mechanical work (upper panel) and mechanical efficiency (lower panel) as a function of shuttle distance at slow (black columns), moderate (grey columns) and maximal (white columns) velocities. Data are means ± SD.

and 15%, respectively (average at all speeds).

Positive and negative power were calculated at maximal velocity only, before and after the CoD; these data are reported in Table 2. On the average (both methods and all distances) P^- amounts to 21.2 ± 4.2 W·kg^{-1} and P^+ to 11.7 ± 2.3 W·kg^{-1}; the former is thus about twice than the latter. The differences between P^+ and P^- depend essentially on differences in the time spent in the acceleration and deceleration phases (t_{acc} and t_{dec}) since total mechanical energy changes ($\Delta E_T{}^+$ and $\Delta E_T{}^-$) are about the same in these two phases (before and after the CoD). The 2-way ANOVA indicates that power output (P^- and P^+) is affected by the method utilized to calculate it (main effect, df = 80; F = 12.5; $p < 0.001$) but that the P^-/P^+ ratio is not (df = 80; F = 9.8; $p = 0.527$). P^+ was found to decrease with the distance covered (main effect, $p = 0.019$) while P^- is not influenced by it (df = 20; F = 10.6; $p = 0.553$) as a consequence the P^-/P^+ ratio increases as a function of shuttle distance (main effect: df = 10; F = 11.2; $p < 0.001$):

Table 2

Average (± SD) values referring to the deceleration/acceleration phases (before/after the CoD) during shuttle runs at maximal velocity. Data were calculated during the entire acceleration or deceleration phases (ΔE_{Tmax}) or by considering a cut off of 5 J·kg^{-1}, corresponding to the last/first step before/after the change of direction (ΔE_T = 5 J·kg^{-1}). See text for details.

	distance m	t_{acc} s	t_{dec} s	ΔE_T^- J·kg^{-1}	ΔE_T^+ J·kg^{-1}	P^- W·kg^{-1}	P^+ W·kg^{-1}
ΔE_{Tmax}	5 + 5	0.96 ± 0.1	0.58 ± 0.09	10.7 ± 1.3	10.89 ± 1.3	18.9 ± 4.0	11.4 ± 2.0
	10 + 10	1.56 ± 0.21	0.87 ± 0.16	16.9 ± 2.4	17.05 ± 2.4	19.9 ± 4.3	11.3 ± 2.6
	15 + 15	2.04 ± 0.28	1.05 ± 0.18	21.6 ± 2.8	21.7 ± 2.8	21.0 ± 4.1	10.9 ± 2.3
	20 + 20	2.51 ± 0.31	1.23 ± 0.16	24.8 ± 4.3	24.9 ± 4.3	20.4 ± 4.5	10.2 ± 2.4
$\Delta E_T = 5\,J{\cdot}kg^{-1}$	5 + 5	0.38 ± 0.07	0.23 ± 0.06	4.7 ± 0.2	4.8 ± 0.1	21.9 ± 5.1	13.0 ± 2.4
	10 + 10	0.38 ± 0.06	0.21 ± 0.05	4.5 ± 0.5	4.6 ± 0.5	22.3 ± 4.4	12.2 ± 2.1
	15 + 15	0.39 ± 0.07	0.21 ± 0.04	4.6 ± 0.3	4.7 ± 0.2	22.4 ± 3.7	12.4 ± 2.1
	20 + 20	0.41 ± 0.10	0.21 ± 0.06	4.6 ± 0.3	4.7 ± 0.2	22.9 ± 6.7	12.1 ± 2.4

CoD: Change of direction; t_{acc}: duration of the acceleration phase; t_{dec}: duration of the deceleration phase; ΔE_T^+: total energy changes during the acceleration phase; ΔE_T^-: total energy changes during the deceleration phase; P^+: positive power output; P^-: negative power output (braking power).

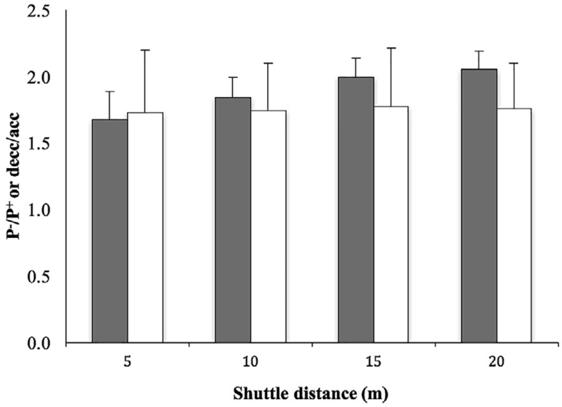

Fig. 4. The ratio of negative to positive power (P^-/P^+; grey columns) and the deceleration/acceleration ratio (*dec/acc*; white columns) in shuttles over different distances covered at maximal speed. Data are means ± SD.

is about 20% larger at 20 + 20 m than at 5 + 5 m (see Fig. 4). No significant interactions were observed (method × distance) for any of these three parameters.

Finally, the average acceleration and deceleration values were calculated at maximal velocity only, before and after the CoD. Average acceleration (*acc*) decreased (df = 20; F = 12.6; $p < 0.001$) as a function of the distance covered: 4.00 ± 0.62 m·s^{-2} (5 + 5 m), 3.35 ± 0.58 m·s^{-2} (10 + 10 m), 2.89 ± 0.46 m·s^{-2} (15 + 15 m) and 2.55 ± 0.42 m·s^{-2} (20 + 20 m) and the values of average deceleration (*dec*) followed a similar trend (P < 0.001): 6.82 ± 1.64 m·s^{-2} (5 + 5 m), 5.73 ± 1.19 m·s^{-2} (10 + 10 m), 5.06 ± 1.22 m·s^{-2} (15 + 15 m) and 4.43 ± 0.89 m·s^{-2} (20 + 20 m). The ratio dec/acc (1.75 ± 0.39) is similar to the P^-/P^+ ratio (1.94 ± 0.46) calculated over the same time interval even if the former does not change as a function of shuttle distance (df = 20; F = 2.9; $p = 0.979$) as the latter (see Fig. 4).

4. Discussion

In this study we investigated mechanical work and power during accelerated and decelerated running in humans by using, as an experimental model, shuttle runs over different distances and at different speeds. Indeed, shuttle runs are characterized by an acceleration phase, a deceleration phase and a change of direction (a 180° turn) and larger accelerations (and decelerations) could be attained either by increasing the velocity or the distance of the shuttle.

4.1. Internal, external and total mechanical work

Data of mechanical work reported in this study are based on the analysis of the time course of potential and kinetic energy of BCoM (W^+_{ext}) and on the computation of the translational and rotational kinetic energy of the body segments (W^+_{int}). We applied these methods in order to compare our data with previously published data on human running and because they have been widely used in human as well as in animal locomotion (Ahn, Furrow, & Biewener, 2004; Cavagna & Kaneko, 1977; Genin, Willems, Cavagna, Lair, & Heglund, 2010; Griffin & Kram, 2000; Pavei, Seminati, Cazzola, & Minetti, 2017; Pellegrini, Zoppirolli, Bortolan, Zamparo, & Schena, 2014; Saibene & Minetti, 2003; Willems et al., 1995). At variance with constant speed linear running, a certain amount of work needs to be performed to rotate the body along its vertical axis during the turns, this work was not taken into account in this paper, and this is a limitation of our study. However, this "additional" mechanical work is performed once in a SR and is expected to have a little influence on the total mechanical wok that is expressed per unit distance. Indeed, no major differences were observed when comparing energy expenditure in SR without turns (only deceleration and acceleration phases in the same direction) or with different turning angles (0, 45, 90 and 180°) (Zamparo et al., 2014).

As hypothesized, and previously found for the energy cost of shuttle running, we observed that total mechanical work (W^+_{tot}): i) increases as a function of velocity for each shuttle distance; ii) at any given velocity is lower the longer the shuttle distance. The largest values of W^+_{int}, W^+_{ext} and W^+_{tot} are indeed observed at maximal velocity and do not greatly differ with shuttle distance (see Fig. 3). Interestingly, the lowest values of W^+_{tot} (at slow speed over the 20 + 20 m distance) are close to those assessed during constant speed, linear running (e.g. Cavagna & Kaneko, 1977) and the same is true for the values of W^+_{int} and W^+_{ext}.

Mechanical work data reported in this study over the shorter shuttle distance (5 + 5 m) are in line with those reported by Zamparo et al. (2016) over the same distance: in agreement with the previous study our data underline that W^+_{int} is a strong determinant of W^+_{tot} and that this parameter could not be neglected, especially during high velocity shuttle running (over all shuttle distances).

4.2. Mechanical efficiency (eff^{+}_{tot})

As indicated in the methods section, the efficiency calculated in this study (eff^{+}_{tot}) is sometimes defined as locomotion efficiency or "apparent" efficiency and does not correspond to the efficiency that can be calculated at the muscle level. Measuring it can help to understand whether mechanical work has been "recycled" via storage and release of elastic energy (e.g. Full, 1991; Lai, Schache, Lin, & Pandy, 2014; Minetti, Ardigò, Reinsch, & Saibene, 1999) thus indicating the presence of an energy saving mechanism (Alexander, 1991).

Data of eff^{+}_{tot} reported in this study over the shorter shuttle distance (5 + 5 m) are in line with those reported by Zamparo et al. (2016); this finding encouraged us to attempt to calculate/estimate mechanical efficiency also over the other distances (no efficiency data are reported in the literature about shuttle runs over longer distances) even if the fact that the energy cost was not directly measured is a limitation of this study.

The large range in eff^{+}_{tot} (from about 0.20 to 0.50, Fig. 3, lower panel) suggests the crucial role of the partitioning between acceleration (pure muscle efficiency ≈0.25–0.30 e.g. Woledge et al., 1985) and 'almost' constant speed ("apparent" efficiency ≈0.5–0.6 Cavagna & Kaneko, 1977) phases during the shuttle run. It is likely that a greater relative importance of the constant speed phase, associated to a better exploitation of the elastic energy saving mechanism, is responsible of the higher "apparent" efficiency at the longer shuttle distances. Moreover, in the acceleration/deceleration phases (especially over the shortest shuttle distances) muscles could contract at sub-optimal length and/or velocity conditions, with a potentially negative influence on their efficiency.

The method to calculate efficiency utilized in this study is based on the ratio between total mechanical work and metabolic energy cost. Total mechanical work estimation is still debated in the literature, as also acknowledged for some aspects by the original authors (Willems et al., 1995). In absence of a closed-form solution in the literature, despite some really knowledgeful attempts (Aleshinsky 1986 a, b, c, d, e) we kept on adding W_{int} and W_{ext} to approximate W_{tot} by considering as only energy transfer the one within body limbs segments. The only components left behind with our approach are the rotational work over the twist axis at change of direction and the internal friction in body tissues, which could affect the total mechanical work done. It has to be considered that efficiency, which is output divided by input, cannot include in the numerator the effects of isometric muscle contraction and co-contraction although their metabolic counterparts are already included in the denominator.

4.3. Mechanical power output

Human and animal locomotion at constant average speed and on the level utilizes equivalent and counterbalancing phases of positive and negative work to maintain an average energy level (e.g. Daley & Biewener, 2003; Rubenson, Heliams, Llyod, & Fournier, 2004; Saibene & Minetti, 2003). Positive and negative work, in both level and non-level gaits, depend on the work generated by muscles or dissipated by muscles and other anatomical structures through either shortening (concentric) or lengthening (eccentric) contractions. During running on the level push time is larger than brake time (at least at speeds lower than 4 m·s^{-1}, as in the present study), whereas total mechanical energy changes (ΔE_T^{+} and ΔE_T^{-}) are about the same (e.g. Cavagna, 2010). This difference in time is generally attributed to the greater muscular force exerted during the eccentric phase. Our data extend these considerations to unsteady locomotion (albeit at maximal velocity only): the time spent in the acceleration phase is larger than that spent in the deceleration phase, over all shuttle distance, whereas positive and negative mechanical energy changes during a SR are essentially the same (see Table 2). To our knowledge these are the first data on braking power in human running reported so far in the literature; indeed, whereas the mechanics of accelerated running (sprints) has been investigated in humans (and animals), braking power received far less attention.

Only data at maximal speeds were considered in these calculations because force (and power) in submaximal runs can be voluntary modulated by the subjects whereas, at maximal speeds, they had to exploit all their muscle force (and power). Our athletes, however, were free to select the "pacing strategy" when covering at top velocity the entire shuttle distance: they preferred to spend more time during the acceleration phase and less time during the deceleration phase probably because in the deceleration phase they could exert greater (eccentric) muscular forces.

The maximal values of (average) acceleration and deceleration were observed over the shortest shuttle distance; over longer distances these values tend to decrease. This could also be appreciated by inspection of Fig. 1 where the slope of the v vs. t curves is a measure of the acceleration/deceleration of the runner. The ascending/descending limbs of the v vs. t curves show the same profile (and at a given time/distance are superimposable) for all shuttle distances and this highlights that runners exploit the same movement pattern when asked to perform at maximal velocity. However, the time to reach maximal velocity is different and this relates to different values of acceleration and deceleration over different shuttle distances.

Finally, our data show that the *dec/acc* ratio (in SR covered at maximal speed and over all distances) is not far from the P^{-}/P^{+} ratio (as measured in the same time interval); this ratio likely depends on the fundamental properties of skeletal muscles in vivo (larger values of force and power in eccentric than in concentric conditions) in agreement with the F vs. v relationship of isolated muscle.

5. Conclusions

Data reported in this study confirm and extend to longer shuttle distances our knowledge about the mechanics of shuttle running (an example of non-steady locomotion in humans): external, internal and total work increase as a function of shuttle speed but decrease as a function of shuttle distance. In addition, data reported in this study indicate that running humans can exert a larger negative than positive power (and a larger deceleration than acceleration) in agreement with the fundamental properties of skeletal muscles in vivo. Finally, the larger values of mechanical efficiency observed at the longer shuttle distance suggest a better exploitation of the elastic energy saving mechanism (i. e. these values are close to those reported for linear running at constant speed) whereas this mechanism seems impaired when the shuttle distance decreases (i.e. where accelerations and decelerations, e.g. non-steady conditions, play a more important role).

Acknowledgement

We would like to thank all the athletes who participated to this study for their patience and kind cooperation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.06.005.

References

Ae, M., Tang, H. P., & Yoki, T. (1992). Estimation of inertia proprieties of the body segment in Japanese athletes. *Biomechanisms, 11*, 23–33.
Ahn, A. N., Furrow, E., & Biewener, A. A. (2004). Walking and running in the red-legged running frog, Kassina maculata. *Journal of Experimental Biology, 207*, 399–410.
Aleshinsky, S. Y. (1986a). An energy 'sources' and 'fractions' approach to the mechanical energy expenditure problem – I. Basic concepts, description of the model, analysis of a one-link system movement. *Journal of Biomechanics, 19*, 287–293.
Aleshinsky, S. Y. (1986b). An energy 'sources' and 'fractions' approach to the mechanical energy expenditure problem – II. Movement of the multi-link chain model. *Journal of Biomechanics, 19*, 287–293.
Aleshinsky, S. Y. (1986c). An energy 'sources' and 'fractions' approach to the mechanical energy expenditure problem – III. Mechanical energy expenditure reduction during one link motion. *Journal of Biomechanics, 19*, 287–293.
Aleshinsky, S. Y. (1986d). An energy 'sources' and 'fractions' approach to the mechanical energy expenditure problem – IV. Criticism of the concept of 'energy transfers within and between links'. *Journal of Biomechanics, 19*, 287–293.
Aleshinsky, S. Y. (1986e). An energy 'sources' and 'fractions' approach to the mechanical energy expenditure problem – V. Mechanical energy expenditure reduction during motion of the multi-link system. *Journal of Biomechanics, 19*, 287–293.
Alexander, R. McN. (1991). Energy saving mechanisms in walking and running. *Journal of Experimental Biology, 160*, 55–69.
Bucheit, M., Haydar, B., Hader, K., Ufland, P., & Ahmaidi, S. (2011). Assessing running economy during field running with changes of direction: Application to 20 m shuttle runs. *International Journal of Sport Physiology and Performance, 6*(3), 380–395.
Buglione, A., & di Prampero, P. E. (2013). The energy cost of shuttle running. *European Journal of Applied Physiology, 113*, 1535–1543.
Cavagna, G. A., & Kaneko, M. (1977). Mechanical work and efficiency in level walking and running. *Journal of Physiology, 268*, 467–481.
Cavagna, G. A. (2010). Symmetry and asymmetry in bouncing gaits. *Symmetry, 2*, 1270–1321.
Daley, M. A., & Biewener, A. A. (2003). Muscle force-length dynamics during level *versus* incline locomotion: A comparison of *in vivo* performance of two guinea fowl ankle extensors. *Journal of Experimental Biology, 206*, 2941–2958.
di Prampero, P. E., Botter, A., & Osgniach, C. (2015). The energy cost of sprint running and the role of metabolic power tin setting top performances. *European Journal of Applied Physiology, 115*, 451–469.
Ettema, G. J. C. (2001). Muscle efficiency: The controversial role of elasticity and mechanical energy conversion in stretch-shortening cycles. *European Journal of Applied Physiology, 85*, 457–465.
Full, R. J. (1991). The concepts of efficiency and economy in land locomotion. In E. W. Blake (Ed.). *Efficiency and Economy in Animal Physiology* (pp. 97–131). Cambridge: Cambridge University Press.
Genin, J. J., Willems, P. A., Cavagna, G. A., Lair, R., & Heglund, N. C. (2010). Biomechanics of locomotion in Asian elephants. *Journal of Experimental Biology, 213*, 694–706.
Griffin, T. M., & Kram, R. (2000). Penguin waddling is not wasteful. *Nature, 408*, 929.
Lai, A., Schache, A. G., Lin, Y. C., & Pandy, M. G. (2014). Tendon elastic strain energy in the human ankle plantar-flexors and its role with increased running speed. *Journal of Experimental Biology, 217*, 3159–3168.
McNarry, M. A., Wilson, R. P., Holton, M. D., Griffiths, I. W., & Mackintosh, K. A. (2017). Investigating the relationship between energy expenditure, walking speed and angle of turning in humans. *Plos One, 12*(8), e0182333. https://doi.org/10.1371/journal.pone.0182333.
Minetti, A. E., Ardigò, L. P., & Saibene, F. (1993). Mechanical determinants of gradient walking energetics in man. *Journal of Physiology, 472*, 725–735 Erratum in: Journal of Physiology (1994) 475, 548.
Minetti, A. E., Ardigò, L. P., Capodaglio, E., & Saibene, F. (2001). Energetics and mechanics of human walking at oscillating speeds. *American Zoologist, 41*, 205–210.
Minetti, A. E., Ardigò, L. P., Reinsch, E., & Saibene, F. (1999). The relationship between mechanical work and energy expenditure of lomotion in horses. *Journal of Experimental Biology, 202*, 2329–2338.
Minetti, A. E., Cazzola, D., Seminati, E., Giacometti, M., & Roi, G. S. (2011). Skyscraper running: Physiological and biomechanical profile of a novel sport activity. *Scandinavian Journal of Medicine and Science in Sports, 21*(2), 293–301.
Minetti, A. E., Gaudino, P., Seminati, E., & Cazzola, D. (2013). The cost of transport of human running is not affected, as in walking, by wide acceleration/deceleration cycles. *Journal of Applied Physiology, 114*, 498–503.
Nagahara, R., Mizutani, M., Matsuo, A., Kanehisa, H., & Fukunaga, T. (2018). Association of sprint performance with ground reaction forces during acceleration and maximal speed phases in a single sprint. *Journal of Applied Biomechanics, 34*, 104–110.
Osgniach, C., Poser, S., Bernardini, R., Rinaldo, R., & di Prampero, P. E. (2010). Energy cost and metabolic power in elite soccer: A new match analysis approach. *Medicine and Science in Sports and Exercise, 42*(1), 170–178.
Pavei, G., & Minetti, A. E. (2016). Hopping locomotion at different gravity: Metabolism and mechanics in humans. *Journal of Applied Physiology, 120*, 1223–1229.
Pavei, G., Seminati, E., Cazzola, D., & Minetti, A. E. (2017). On the estimation accuracy of the 3D body center of mass trajectory during human locomotion: Inverse vs. forward dynamics. *Frontiers in Physiology, 8*, 129. https://doi.org/10.3389/fphys.2017.00129.
Pellegrini, B., Zoppirolli, C., Bortolan, L., Zamparo, P., & Schena, F. (2014). Gait models and mechanical energy in three cross country skiing techniques. *Journal of Experimental Biology, 217*, 3910–3918.
Peyré-Tartaruga, L. A., & Coertjens, M. (2018). Locomotion as a powerful model to study integrative physiology: Efficiency, economy and power relationship. *Frontiers in Physiology, 9*, 1789. https://doi.org/10.3389/fphys.2018.01789.
Rubenson, J., Heliams, D. B., Lloyd, D. G., & Fournier, P. A. (2004). Gait selection in the ostrich: Mechanical and metabolic characteristics of walking and running with and without an aerial phase. *Proceedings of the Royal Society B, 271*, 1091–1099.
Saibene, F., & Minetti, A. E. (2003). Biomechanical and physiological aspects of legged locomotion in humans. *European Journal of Applied Physiology, 88*(4–5), 297–316.
Slawinski, J., Termoz, N., Rabita, G., Guilhem, G., Dorel, S., Morin, J. B., & Samozino, P. (2017). How 100-m event analyses improve our understanding of world class

men's and women's sprint performance. *Scandinavian Journal of Medicine and Science in Sports, 27*(1), 45–54.

Stevens, T. G., De Ruiter, C. G., Van Maurik, D., Van Lierop, C. J., Savelsbergh, G. J., & Beek, P. J. (2015). Measured and estimated energy cost of constant and shuttle running in soccer players. *Medicine and Science in Sports and Exercise, 47*, 1219–1224.

Taylor, J. B., Wright, A. A., Dischiavi, S. L., Towsend, M. A., & Marmon, A. R. (2017). Activity demands during multidirectional team sports: A systematic review. *Sports Medicine, 47*, 2533–2551.

Willems, P. A., Cavagna, G. A., & Heglund, N. C. (1995). External, internal and total work in human locomotion. *Journal of Experimental Biology, 198*, 379–393.

Wilson, J. W., Mills, M. G. L., Wilson, R. P., Peters, G., Mills, M. E., Speakman, J. R., ... Scantlebury, M. (2013). Cheetahs, Acinonyx jubatus, balance turn capacity with pace when chasing prey. *Biology Letters, 9*(5), 20130620. https://doi.org/10.1098/rsbl.2013.0620.

Wilson, R. P., Griffiths, I. W., Legg, P. A., Friswell, M. I., Bidder, O. R., Halsey, L. G., ... Shepard, E. L. (2013). Turn costs change the value of animal search paths. *Ecology Letters, 16*(9), 1145–1150.

Wilson, R. P., Griffiths, I. W., Mills, G. L., Carbone, C., Wilson, J. W., & Scantlebury, M. (2015). Mass enhances speed but diminishes turn capacity in terrestrial pursuit predators. *eLife, 4*. https://doi.org/10.7554/eLife.06487.

Woledge, R. C., Curtin, N. A., & Homsher, E. (1985). *Energetic aspects of muscle contraction.* London: Academic Press.

Zadro, I., Sepulcri, L., Lazzer, S., Fregolent, R., & Zamparo, P. (2011). A protocol of intermittent exercise (shuttle runs) to train young basketball players. *Journal of Strength and Conditioning Research, 25*, 1767–1773.

Zamparo, P., Zadro, I., Lazzer, S., Beato, M., & Sepulcri, L. (2014). Energetics of shuttle runs: The effects of distance and change of direction. *International Journal of Sports Physiology and Performance, 9*, 1033–1039.

Zamparo, P., Bolomini, F., Nardello, F., & Beato, M. (2015). Energetics (and kinematics) of short shuttle runs. *European Journal of Applied Physiology, 115*, 1985–1994.

Zamparo, P., Pavei, G., Nardello, F., Bartolini, D., Monte, A., & Minetti, A. E. (2016). Mechanical work and efficiency of 5 + 5 m shuttle running. *European Journal of Applied Physiology, 116*, 1911–1919.