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ORIGINAL ARTICLE

The bouncing mechanism of running against hindering, or with aiding traction forces: a comparison with running on a slope

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Abstract

Purpose Much like running on a slope, running against/with a horizontal traction force which either hinders/aids the forward motion of the runner creates a shift in the positive and negative muscular work, which in turn modifies the bouncing mechanism of running. The purpose of the study is to (1) investigate the energy changes of the centre of mass and the storage/release of energy throughout the step during running associated with speed and increasing hindering and aiding traction forces; and (2) compare these changes to those observed when running on a slope.

Methods Ground reaction forces were measured on eight subjects running on an instrumented treadmill against different traction forces at different speeds.

Results As compared to unperturbed running, running against/with a traction force increases/decreases positive external work by ~ 20–70% and decreases/increases negative work by ~ 40–60%, depending on speed and traction force. The external power to maintain forward motion against a traction is contained by increasing the pushing time and step frequency. When running with an aiding force, the external power during the brake is limited by increasing braking time. Furthermore, the aerial time is increased to reduce the power required to reset the limbs each step.

Conclusion Our results show that the bouncing mechanism of running against/with a hindering/aiding traction force is equivalent to that of running on a positive/negative slope.

Keywords Body centre of mass · Locomotion · External work · Pulling force · Propulsive and braking force

Abbreviations

a_l, a_f, a_v	Lateral, fore-aft and vertical accelerations of the *CoM*
$\overline{a}_{v,ce}$, $\overline{a}_{v,ae}$	Average vertical acceleration of the CoM during the t_{ce} and t_{ae}
ATF, HTF	Aiding traction force, hindering traction force
BW	Body weight
$BW_{//}$	Component of the body weight vector parallel to the slope of the terrain
CoM	Centre of mass of the body
$E_{com} = E_{kf} + E_v$	Mechanical energy of the CoM due to its movements relative to the surroundings
E_{kf}	Kinetic energy of the CoM due to its fore-aft velocity
E_v	Mechanical energy of the CoM due to its vertical movements
f_s	Natural frequency of the body bouncing system
$\overline{F}_{brake}$, $\overline{F}_{push}$	Average forces during the negative (brake) and positive (push) work phases
F_f	Resultant of the fore-aft forces applied on the body
F_{tr}	Horizontal component of the traction force

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F_l, F_h, F_v	Lateral, horizontal and vertical components of the *GRF*
$\overline{F}_h$	Average of F_h over a stride
$\overline{F}_v$	Average of F_v over a stride
g	Acceleration of gravity
GRF	Ground reaction force
k	Stiffness of the elastic structures responsible for the rebound
m	Body mass
$\overline{P}_f$	Average power spent to maintain the fore-aft movements of the CoM
$\overline{P}_s$	Average power spent on a slope
$\overline{P}_{tr}$	Average power spent to overcome the traction force
$\overline{P}_v$	Average power spent to maintain the vertical movements of the CoM
$\%R$	Percentage of energy transduction between E_v and W_f
s_v	Vertical displacement of the CoM
T	Step period
t_{ae}, t_{ce}	Effective aerial time and effective contact time, i.e., respectively, the period during which $F_v < \text{BW}$, and $F_v > \text{BW}$
t_a, t_c	Aerial time and contact time
t_{push}, t_{brake}	Duration of W_{ext}^+ and W_{ext}^-
Unperturbed running	Running on the level at a constant average speed, without a traction force
v_{belt}	Speed of the treadmill belt
V_{belt}	Average speed of the treadmill belt over a stride
v_l, v_f, v_v	Lateral, fore-aft, and vertical components of the velocity of the CoM
$\overline{v}_f$	Average of v_f over a stride
$\overline{v}_v$	Average of v_v over a stride
W_{ext}	External work, i.e., the work done to sustain the movements of the CoM relative to the surroundings plus the work done on/by the traction force
W_{ext}^+, W_{ext}^-	Positive and negative work phases of W_{ext}
$\dot{W}_{ext}$	External power, i.e., the time-derivative of W_{ext}
$\dot{W}_{int}$	Internal power, i.e., the power necessary to move the limbs relative to CoM
W_f	Work done at each instant to sustain the fore-aft movements of the CoM plus the work to overcome the traction force
W_f^+,W_f^-	Positive and negative work phases of W_f
W_v^+,W_v^-	Positive and negative work done to sustain the vertical movements CoM relative to the surroundings
W_{tr}	External work done on/by the traction force

Introduction

When running on the level on firm ground, since the foot is not skidding and wind resistance is negligible, muscles perform as much positive as negative external work to move the body relative to the environment (Cavagna et al. 1976). In this situation, the movement of the centre of mass of the body (CoM) can be compared to a mass mounted on a spring, bouncing on the ground (Cavagna et al. 1988). When running uphill or downhill, positive and negative muscular works done are not anymore equal (Minetti et al. 1994), since gravitational potential energy of the CoM must be increased/decreased each step due to slope. This unbalance between positive and negative external work modifies the bouncing mechanism of running (Dewolf et al. 2016).

As running on a slope, running at a constant speed with a horizontal traction force which either hinders or aids the forward motion of the subject will also disturb the ratio of positive and negative work done. This unbalance will most likely also modify the bouncing mechanism of running. Indeed, in this case, muscles must perform/dissipate additional work each step to maintain the average kinetic energy of the CoM constant.

To the best of our knowledge, no studies have examined the bouncing mechanism while running either with or against a horizontal force. The purpose of this study is to analyse the changes in the bouncing mechanism of running brought about by an aiding/hindering horizontal force. Therefore, we used a subject pulling system that generates a horizontal aiding (ATF) or hindering (HTF) force of 5–15% of body weight (BW). We expect the four following characteristics of the bouncing mechanism to be affected by the horizontal force.

First, when running with an HTF/ATF, the CoM tends to decelerate/accelerate during the step and muscles must produce/dissipate energy to keep the average speed of progression constant. We hypothesise that, on one hand, the unbalance between positive and negative work done to sustain the motion of the CoM (W_{ext}^+ and W_{ext}^-) will, to a certain extent, jeopardise the bouncing mechanism of running. On the other hand, we hypothesise that, when running against an HTF, the reduction of the negative work will restrain the increase in positive external work due to traction. The contrary will be true during running with an ATF: a reduction of the positive work will limit the increase in the negative work due to traction. In other words, the amount of energy that can be stored and released in the elastic structures of the lower limb will be reduced when the traction increases either forwards or backwards.

Second, during running, the vertical movements of the CoM can be compared to a mass mounted on a spring that bounces on the ground. From a mechanical point of view, this spring–mass system oscillates around an equilibrium point at which the vertical component of the GRF (F_v) is equal to body weight (BW) (Cavagna et al. 1988). The natural frequency of the bouncing system (f_s) depends on the body mass (m) and the stiffness of the elastic structures responsible for the rebound (k): $f_s = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$. At all running speeds, the period t_{ce} represents the duration of half the period of the oscillation of the bouncing system, i.e. $t_{ce} = \pi\sqrt{\frac{m}{k}}$. The period t_{ae} represents the other half of the oscillation of the bouncing system only if the aerial phase is nil. Indeed, if the body leaves the ground, the elastic model is no longer valid, because the restoring force is no longer proportional to the displacement (since the vertical acceleration is constant).

When running on the level, the vertical momentum lost and gained during t_{ce} must equal the vertical momentum lost and gained during t_{ae}. Consequently:

$$\overline{a}_{v,ce} t_{ce} = \overline{a}_{v,ae} t_{ae}, \tag{1}$$

where $\overline{a}_{v,ce}$ and $\overline{a}_{v,ae}$ are the average vertical accelerations during t_{ce} and t_{ae}, respectively. At slow speeds, $\overline{a}_{v,ce} = \overline{a}_{v,ae}$ and the rebound is symmetric, i.e., $t_{ce} \approx t_{ae}$ (called the *on–off* ground symmetry, Cavagna 2009). At speeds around 3–3.5 m s^{-1}, $\overline{a}_{v,ce}$ becomes greater than 1 g; whereas $\overline{a}_{v,ae}$ cannot exceed 1 g. Consequently, $t_{ae} > t_{ce}$ and the step becomes asymmetric (Cavagna et al. 1988; Schepens et al. 1998). For a given t_{ce}, an on–off ground symmetry requires a smaller $\overline{a}_{v,ce}$, which in turn reduces the external power ($\dot{W}_{ext}$) to move the CoM relative to the environment (Cavagna et al. 1991), whereas an on–off ground asymmetry requires a greater $\overline{a}_{v,ce}$; however, due to a longer t_{ae}, the step period is increased and results in a smaller internal power ($\dot{W}_{int}$) necessary to reset the limbs at each step (Cavagna et al. 1988).

As compared to unperturbed running, running with/against a traction force requires additional external positive/negative power to overcome the traction force. We hypothesise that this situation will be similar to running on a positive/negative slope. Therefore, to limit the increase in $\dot{W}_{ext}$, we expect that, when running against an HTF, the step will remain symmetric above 3–3.5 m s^{-1} (Dewolf et al. 2016). In contrast, when running with an ATF, we expect—because maximal muscle forces are greater during eccentric than concentric contractions—that t_{ae} becomes greater than t_{ce} at speeds lower than 3–3.5 m s^{-1}. In other words, we hypothesise that with an ATF the on–off ground asymmetry appears at lower speeds. In this way, the time to reset the limbs is increased and, therefore, the $\dot{W}_{int}$ during the swing phase—rather than the $\dot{W}_{ext}$—is limited as compared to unperturbed running (Cavagna 2009).

Third, if an unbalance between $W_{ext}{}^{+}$ and $W_{ext}{}^{-}$ is present, we expect that the duration of the negative (brake) and positive (push) work phases (respectively t_{brake} and t_{push}) will be modified, as compared to unperturbed running. While the spring–mass system assumes the same characteristics of the spring during the storage and release of energy, i.e., a ratio t_{brake}/t_{push} equal to 1, an asymmetry between the braking and pushing time reflects a deviation from the elastic behaviour of the spring–mass model (Cavagna 2006; Dewolf and Willems 2017, 2019; Maykranz and Seyfarth 2014). When a traction force hinders the forward movement of the CoM, we hypothesise that the duration of t_{brake} will be shortened, while that of t_{push} will be lengthened to contain the increase in $\dot{W}^{+}_{ext}$. In this case, the ratio t_{brake}/t_{push} would tend towards zero when the running speed and the traction force increase. In contrast, when the subject is being aided in his movement, the duration of t_{push} will be shortened and t_{brake} lengthened to contain the increase in $\dot{W}^{-}_{ext}$. In this case, the ratio t_{brake}/t_{push} would become greater than 1 when the running speed and the traction force increase.

Fourth, without traction, the energy fluctuations of the CoM due to its fore-aft movements (E_{kf}) and those due to its vertical movements (E_v) are in phase (Cavagna et al. 1976). Consequently, there is little possibility for energy transduction between the E_{kf}- and the E_v-curves. When running with a hindering/aiding traction force, we expect that the moment at which E_v is minimal will occur around mid-stance, as in unperturbed running. However, the moment at which E_{kf} is minimal will change with the direction and the amplitude of the traction force: this minimum will shift towards touch-down with an increasing hindering force, and towards the take-off with an increasing aiding force. Consequently, an energy exchange can occur between the minimum of these two curves (Cavagna et al.2008a), which could reduce the external work (W_{ext}), hence increasing the %Recovery (%R), as defined by Cavagna et al 2008a (see below and Eq. 11).

To test these four hypotheses, the rebound of the body was analysed on eight subjects running on a treadmill at different speeds with backward/forward traction forces of different magnitudes. Then, the mechanism of running—where the average orientation of the GRF is tilted to counteract the hindering/aiding force—is compared to that of running on a slope—where the angle between the average GRF and the terrain is also modified (Dewolf et al. 2016; Gottshcall and Kram 2005).

Materials and methods

Subjects and experimental procedure

Eight recreational male runners participated in the study. They were all students at the UCLouvain-Belgium (average age: 20.94 ± 1.57 years). Their mass was comprised between 60 and 85 kg (mean ± SD: 72.76 ± 5.57 kg) and their height between 1.7 and 1.9 m (1.81 ± 0.05 m). Informed written consent was obtained. Studies followed guidelines of the Declaration of Helsinki and all procedures were accepted by the UCLouvain (B403201838331).

All subjects ran on an instrumented treadmill at five different constant speeds of: 2.22, 2.78, 3.33, 3.89, and 4.44 m s $^{-1}$ (which corresponds to 8, 10, 12, 14, and 16 km h $^{-1}$), while being pulled by an HTF/ATF. The magnitudes of the traction force were selected to be able to compare the present results with those obtained while running on a slope in Dewolf et al. (2016). When standing on a slope, the BW vector can be broken down into a component perpendicular and another parallel ($BW_{//}$) to the ground. Here, the magnitudes of traction force represented 0%, 5%, 10%, and 15% of BW, which corresponded to $BW_{//}$, i.e., to the sine of the studied slopes (0°, 3°, 6°, and 9°). To remove the effect of learning and of fatigue, the magnitude of the traction was selected in a different order for each subject; then, for each traction, the speeds were selected randomly.

Experimental setup

Experiments were conducted on a commercial treadmill (h/p/Cosmos, Germany) with a belt surface of 1.6 × 0.65 m. The entire treadmill was mounted onto four strain-gage force transducers (Arsalis, Belgium). Because the whole body of the treadmill (including the motor) was mounted on the transducers, these were measuring the three components of the GRF exerted by the treadmill under the foot (Willems and Gosseye 2013). The signal was amplified, low-pass filtered (four-pole Bessel filter with a − 3 dB cut-off frequency at 200 Hz).

The electrical motor of the belt was instrumented with an optical angle encoder to measure the speed of the belt (v_{belt}). The average speed of the belt over a stride (V_{belt}) differed by 2.8 ± 1.4% from the chosen speed and the instantaneous v_{belt} did not change by more than 5% of V_{belt}.

The traction system was similar to the ones proposed by Asmussen and Bonde-Petersen (1974), and by Lloyd and Zacks (1972). The horizontal traction force was generated by a weight attached to a harness via an elastic rope and a pulley. The point of application of the rope on the harness was located at ~ 60% of the subject's height from the ground (i.e., close to the centre of gravity of the projected area of the body on the coronal plane). The pulley was mounted on a force transducer that measured the traction force (F_{tr}). To keep the rope horizontal despite the vertical movements of the runner, the pulley was placed at the level of the fixation point on the harness, 3 m behind/in front of the subject. In this way, the angle between the rope and the horizontal varied by less than ± 2°. Therefore, the change in this angle was not taken into account. Due to friction and inertia, F_{tr} varied within ± 0.5% BW during a step.

The lateral (F_l), fore-aft (F_h), and vertical (F_v) components of *GRF* and the traction force (F_{tr}) were digitized by a 16-bit analogue-to-digital converter at a sampling frequency of 1 kHz. Acquisition and data processing were performed via custom made programs using LABVIEW (National Instruments 2014, Austin, Texas, USA).

Data analysis

All trials analysed began with a right step. Strides were divided according to the beginning of t_{ce}, i.e. when F_v becomes greater than BW (Dewolf et al. 2016). Foot contact was determined at a threshold of $F_v > 10$ N. During trials, between 4 and 32 steps were analysed per condition, and for all subjects, a total of 6324 steps were analysed (Padulo et al. 2014).

Acceleration, velocity, and vertical displacement of the CoM

Calculations for the acceleration, velocity, and displacement of the CoM were done as seen in Padulo et al. (2014) and in Gosseye et al. (2010). Therefore, this method is only explained in brief. Since air friction was negligible, the three forces applied to the body were the body weight (BW), the GRF, and the traction force (F_{tr}). Acceleration in the lateral (a_l), fore-aft (a_f), and vertical (a_v) directions was obtained by:

$$a_l = \frac{F_l}{m}, \tag{2}$$

$$a_f = \frac{F_f}{m} = \frac{F_h + F_{tr}}{m}, \tag{3}$$

$$a_v = \frac{F_v - \overline{F_v}}{m}, \tag{4}$$

where m is the body mass, F_f is the resultant force of F_h and F_{tr}, $\overline{F_v}$ is the average vertical force over a stride. When running on a flat terrain, $\overline{F_v} \approx BW$; if $\overline{F_v}$ varied from BW by more 5%, the stride was not analysed.

Accelerations were time-integrated by the trapezoidal method to determine the variations of vertical (v_v), fore–aft (v_f), and lateral (v_l) velocities of the CoM plus an integration constant. In the fore-aft direction, since the subject was running at an average constant speed, the integration constant was considered to be equal to the average speed of the belt over a stride (V_{belt}). In the lateral and vertical direction, the integration constants of v_l and v_v were equal to zero, on the assumption that the CoM returns to its initial lateral position and height at the end of each stride. The vertical displacement of the CoM (s_v) was then computed by time integration of v_v. A typical trace of F_v, F_h, and F_{tr} and of v_v and v_f is presented in Fig. 1.

Energy of the CoM, external work, and %recovery

The energy of the CoM with respect to the environment (E_{com}, Fig. 2) was calculated as the algebraic sum of the energy due to the vertical movements, E_v, and that due to the fore-aft movements, E_{kf} (Schepens et al. 1998):

$$E_{com} = E_v + E_{kf}, \tag{5}$$

where

$$E_v = mgs_v + \frac{1}{2}mv_v^2, \tag{6}$$

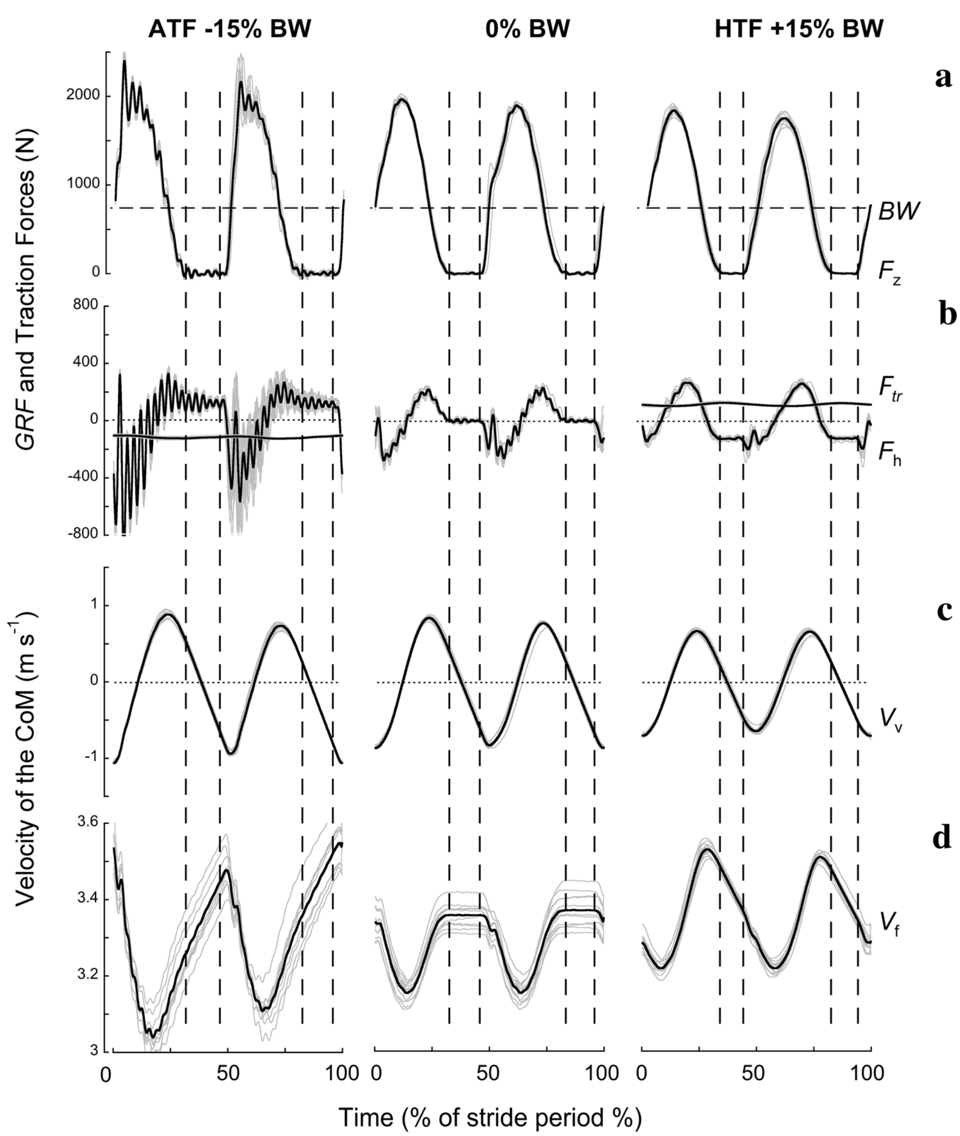


Fig. 1 Time-traces of **a** the vertical (F_v) and **b** fore–aft (F_h) components of ground reaction force and of **c** the vertical (V_v) and **d** fore–aft (V_f) components of the velocity of the CoM. The black lines are obtained by averaging all the consecutive steps (light grey lines) of a subject (mass 77.8 kg, height 1.85 m) running at 3.3 m s^{-1} with no traction force (0% BW), with an ATF (− 15% BW) or an HTF (+ 15% BW). The time is expressed as a percentage of the stride period (T, which equals 0.751 s at 0% BW, 0.739 s at − 15% BW and 0.665 s at + 15% BW). These traces were cut according to the beginning of t_{ce} and filtered by an eighth-order Bessel filter with a cut-off frequency of 25 Hz. The vertical striped lines represent the aerial phase in each step. In panel **a**, the horizontal dotted line indicates the body weight, BW. In panel **b**, F_{tr} is the traction force. Note that when running with an HTF/ATF, the fore–aft velocity of the CoM decreases/increases during the aerial phase, since the traction force is pulling the runner backwards/forwards

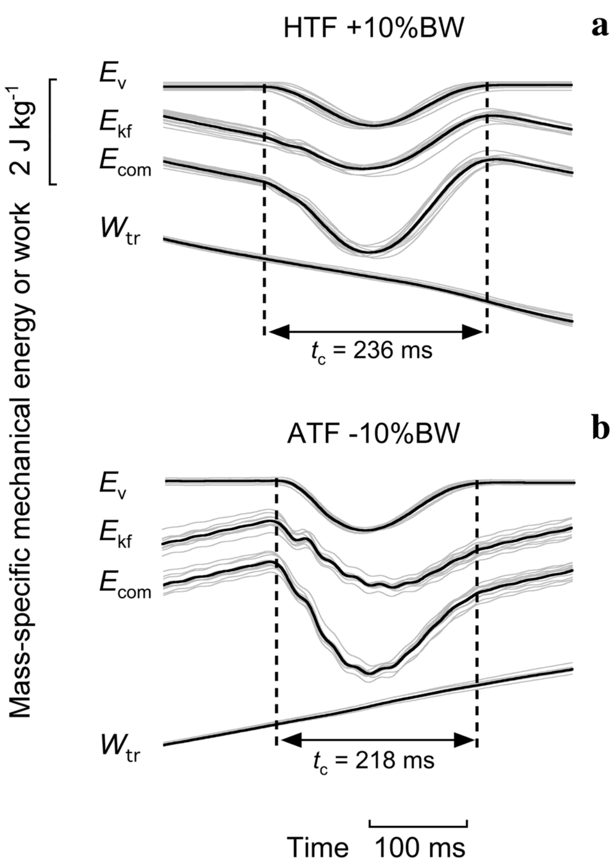


Fig. 2 Typical traces of the mass-specific mechanical energy or work while running at 3.9 m s^{-1} against an HTF (**a**) and with an ATF (**b**). From top to bottom, curves represent the energy of the CoM due to its vertical movements (E_v) and to its fore–aft movements (E_{kf}). The curve E_{com} represents the total energy of the CoM ($E_{com} = E_v + E_{kf}$) and W_{tr} is the work done by/against the traction force. The vertical dotted lines delimit the contact phase. Same subject as in Fig. 1. Other indications as in Fig. 1

$$E_{kf} = \frac{1}{2} m v_f^2. \tag{7}$$

The energy due to the lateral movement of the CoM was neglected (Cavagna et al. 1963). Since the work done by the foot on the belt accounted for less than 3% of E_{com}, it was not considered in this study.

Along the fore–aft axis, even when running without any traction force (unperturbed running), the interaction of the foot with the ground induces a deceleration of the CoM during the first part of the contact phase, which requires to reaccelerate the CoM during the second part of the contact. When running with an HTF/ATF, work must be done during the contact phase not only to sustain the kinetic energy changes of the CoM but also to counteract the traction force. The work done on/by the traction force (Fig. 2) was calculated as:

$$W_{tr} = \int F_{tr} v_{belt} dt, \tag{8}$$

and the work done at each instant to sustain the movements of the CoM in the fore-aft direction (W_f) as the sum of the E_{kf} and the W_{tr} curves:

$$W_f = E_{kf} + W_{tr}. \tag{9}$$

In turn, the work done by the forces applied externally to the body (W_{ext}) was computed as the algebraic sum of the E_v and the W_f curves:

$$W_{ext} = E_v + W_f. \tag{10}$$

Positive (W_f^+, W_v^+ and W_{ext}^+) and negative (W_f^-, W_v^- and W_{ext}^-) works were computed by summing the increments and the absolute value of the decrements of the W_f, E_v, and W_{ext} curves, respectively. Energy transduction between E_v and W_f was assessed as %R (Cavagna et al. 2008a):

$$\%R = \frac{W_f^+ + \left|W_f^-\right| + W_v^+ + \left|W_v^-\right| - \left(W_{ext}^+ + W_{ext}^-\right)}{W_f^+ + \left|W_f^-\right| + W_v^+ + \left|W_v^-\right|}. \tag{11}$$

Statistics

All of the step data from one condition were averaged per subject to obtain the grand average and grand standard deviation which was then grouped into traction and speed classes. To analyse the effect speed and traction on their interaction, a two-way ANOVA with Bonferroni post hoc correction was used (PASW Statistics, 19, SPSS, IBM, Armonk, NY, USA).

We estimated the minimal numbers of strides required to minimise the type I error for the 7 traction classes ($\alpha = 0.05$, $1-\beta = 0.2$, f size = 0.25) using an a priori G*Power test (Faul et al. 2007). Each traction class should totalise at least 224 strides. When running this same test for the 5 speed classes, the number of strides analysed should be higher than 195 in the same conditions. Note that our sample size for the seven traction classes or for the five speed classes is equal to 276.

Results

Positive and negative work done

When running without a traction force, the E_v- and E_{kf}-time curves vary in phase and $W_{ext}^+ = W_f^+ + W_v^+$. Furthermore, muscles are doing as much positive as negative work and $W_v^+ \approx W_v^-$, $W_f^+ \approx W_f^-$ and $W_{ext}^+ \approx W_{ext}^-$. When

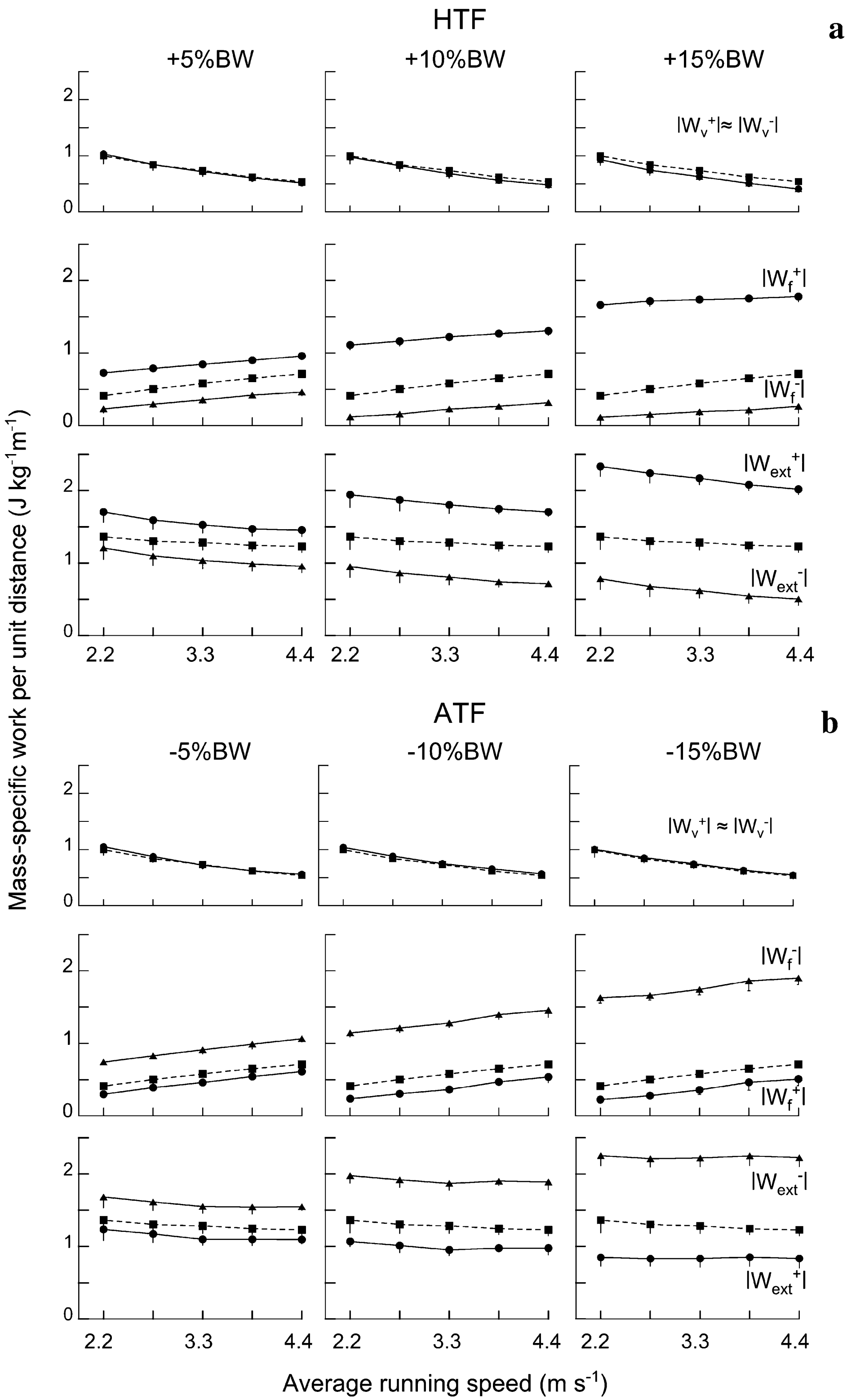


Fig. 3 Mass-specific mechanical work per unit distance (J kg^{-1} m^{-1}). Each traction force displays positive (closed circles, superscript +) and negative (closed triangles, superscript −) mechanical work done each step as a function of speed. The striped line on each graph represents the corresponding positive and negative work on when running without an additional horizontal traction force. W_v is the work done to sustain the vertical movements of the CoM, W_f is the work done to sustain its fore-aft movements, and W_{ext} is the work to maintain the movement of the CoM relative to the surroundings. Since the subject is running on the level, $|W_v^+| = |W_v^-|$. Against an HTF (**a**), there is more $|W_f^+|$ than $|W_f^-|$. Consequently, $|W_{ext}^+| > |W_{ext}^-|$. Against an ATF (**b**), more $|W_f^-|$ than $|W_f^+|$ is being done. Consequently, $|W_{ext}^+| < |W_{ext}^-|$. Symbols and bars represent the grand mean of the subjects ($n = 8$) and the standard deviations (when bars extended beyond the symbols), respectively. These data were plotted via Kaleidagraph 4.5. Note that when running unperturbed, W_{ext}^+ and W_{ext}^- are about equal at all speeds, as in Willems et al. (1995)

running with a traction force, W_v^+ is still approximately equal to W_v^- (Fig. 3) and both decrease with increasing speed against all traction forces. At + 15% *BW*, $W_v^{+/-}$ are significantly lower than during unperturbed running (for both W_v^+ and W_v^-: post hoc Bonferroni $p < 0.001$).

Contrary to W_v^+ and W_v^-, both W_f^+ and W_f^- increase as a function of speed at all traction forces (W_f^-: $F=155.6$, $p<0.001$; W_f^+: $F=192.7$, $p<0.001$). When running against an HTF, W_f^- decreases ($F=3810.8$ $p<0.001$) and W_f^+ increases ($F=3710$, $p<0.001$), as compared to unperturbed running. When running with an ATF, the opposite is true: W_f^- increases with the magnitude of F_{tr}, whereas W_f^+ decreases (in both cases, $F=3811$, $p<0.001$). Consequently, the gap between W_f^- and W_f^+ becomes larger when the magnitude of F_{tr} augments.

The external works W_{ext}^+ and W_{ext}^- decrease slightly with increasing speed (W_{ext}^+: F = 20.26, $p<0.001$; W_{ext}^-: F = 17.56, $p<0.001$). As the magnitude of the F_{tr} increases, the difference between W_{ext}^- and W_{ext}^+ becomes larger (Fig. 3).

Duration of the different phases of step

When running without a traction force, the step period (T) decreases with speed (Fig. 4a) and the on–off asymmetry (i.e., $t_{ae} > t_{ce}$) occurs at speeds above 3–3.5 m s^{-1}, as in Cavagna (2009). When running with an HTF, T decreases significantly as compared to running without traction, due to a shortening of the aerial time (t_a) ($F=7.90$, $p<0.001$). In contrast, when running with an ATF, T does not vary, because contact time (t_c) decreases ($F=4.01$, $p<0.001$), whereas t_a increases ($F=29.09$, $p<0.001$; Fig. 4a) with the increasing traction.

When running with a traction force, as compared to unperturbed running, the relationship between t_{ce} and traction force is not modified ($F=1.805$, $p>0.05$). When the magnitude of HTF augments, t_{ae} decreases ($F=12.48$, $p<0.01$) and tends towards t_{ce}. At + 10% & + 15% BW,

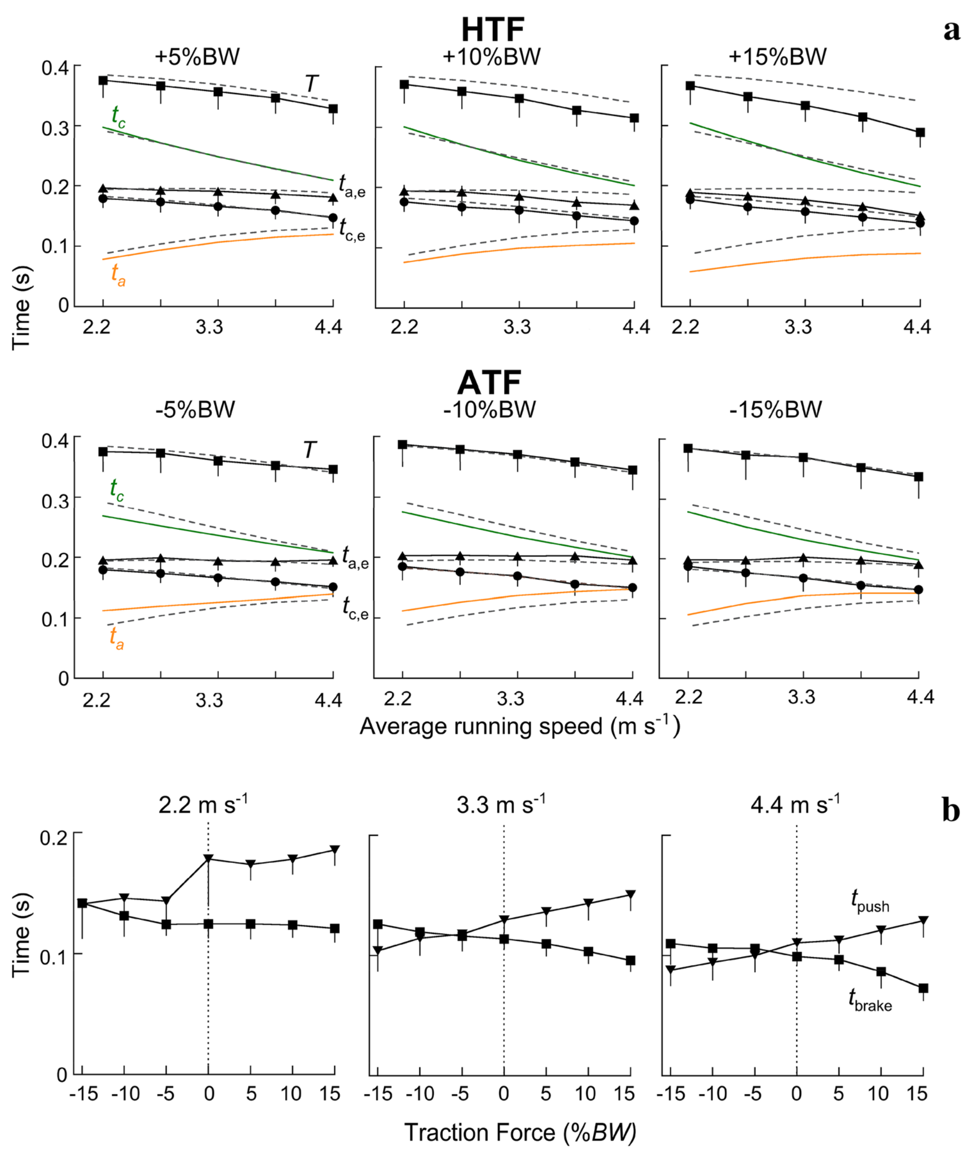


Fig. 4 **a** Step durations as a function of speed at each traction force. Step period T (closed squares), effective aerial time t_{ae} (closed triangles), and effective contact time t_{ce} (closed circles) are shown in black. The green and orange curves are weighted mean (Kaleidagraph 4.5) of the contact t_c and aerial t_a time, respectively. The interrupted lines were fitted through the data obtained when running unperturbed. **b** Time required to brake (t_{brake}, closed squares) and accelerate (t_{push}, closed triangles) the CoM as a function of traction force when running at 2.2, 3.3, and 4.4 m s^{-1}. Other indications as in Fig. 3. Note that when running unperturbed, results obtained on step durations (T, t_{ce}, t_{ae}, t_c, and t_a) are similar to those of Cavagna (2005)

$t_{ce} = t_{ae}$ at all speeds. Oppositely, at any magnitude of ATF, t_{ae} does not change with speed, as compared to unperturbed running.

When running against an HTF, $t_{push} > t_{brake}$ at all speeds; however, the difference between t_{push} and t_{brake} decreases as speed increases. When running with an $|ATF| > 5\%$ *BW* at speeds greater than ~2.2 m s^{-1}, $t_{brake} > t_{push}$ signifying that the subjects spend more time braking than accelerating the CoM forwards.

Energy transduction

When running without any traction force, since air friction is negligible, E_{kf} does not change during the aerial phase and the E_v- and E_{kf}-curves change in phase during contact. When running against/with a traction force, as muscles are not able to counter F_{tr} when the feet are not on the ground, E_{kf} decreases/increase during the aerial phase (Fig. 2). Therefore, during contact, muscles must compensate the loss/gain in E_{kf} and $W_f^+ > W_f^-$ (or $W_f^+ < W_f^-$); this modification causes a shift between the minimums of the E_v- and E_{kf}-curves.

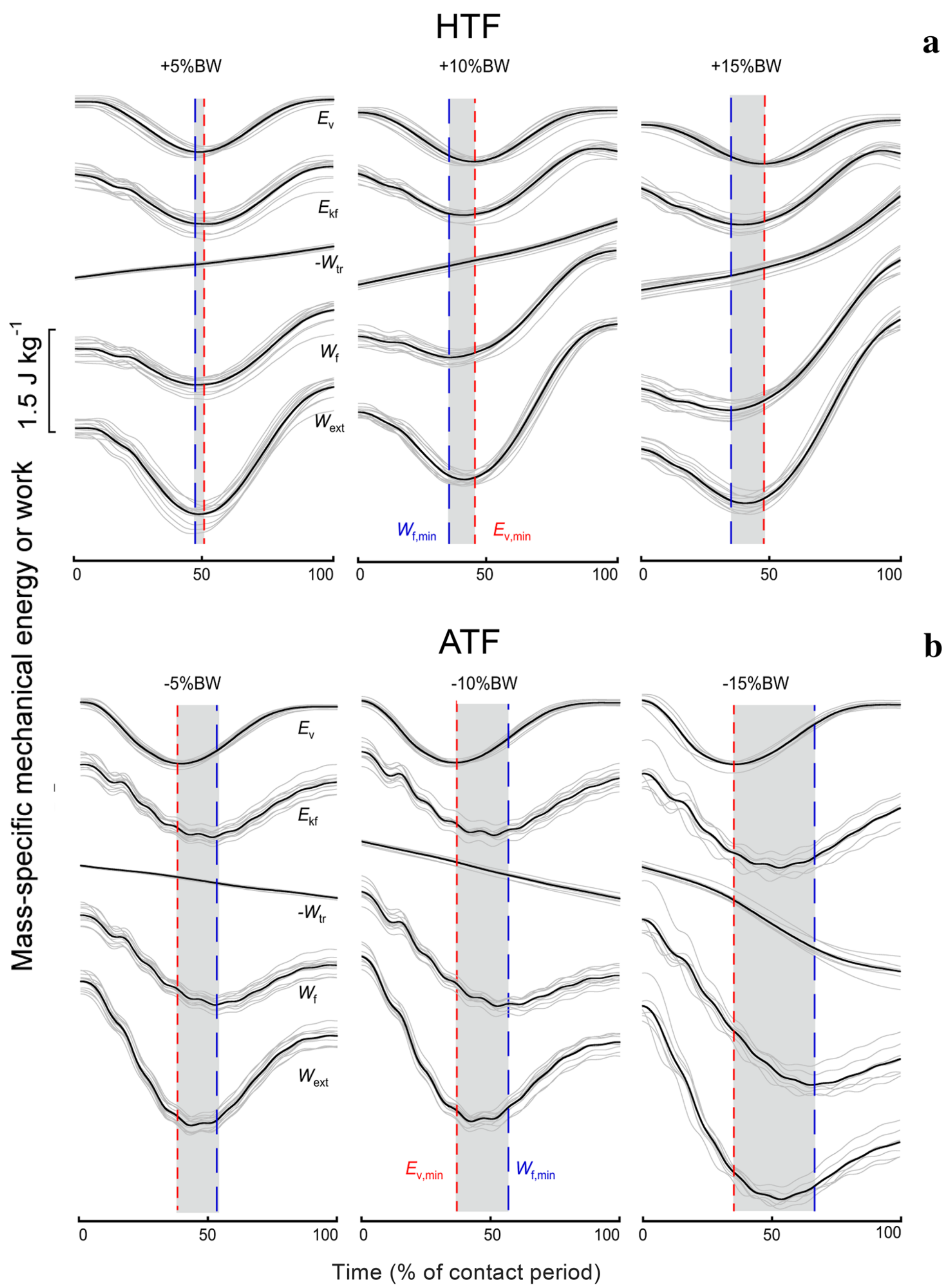


Fig. 5 Typical time-traces of the mass-specific mechanical energy or work while running at 3.9 m s^{-1} against an HTF (**a**) and with an ATF (**b**). The upper three panels display from left to right an increasing HTF (+5%, +10%, +15% BW). The bottom three panels depict an increasing ATF (– 5%, – 10%, – 15% BW). From top to bottom, curves represent the energy of the CoM due to its vertical movements (E_v) and to its fore–aft movements (E_{kf}). The curve $-W_{tr}$ is the work done by the subject to counteract the traction force; W_f is the work done to maintain the forward motion of the CoM and W_{ext} is work done by the muscles to maintain the movements of the CoM relative to the surroundings. The dashed dark blue and red vertical lines represent respectively the minima of W_f and E_v (respectively, $W_{f,min}$ and $E_{v,min}$). Note that against an HTF, $W_{f,min}$ precedes $E_{v,min}$, whereas it follows $E_{v,min}$ with an ATF. The greyed area between the two dashed lines corresponds to the period in which energy transduction takes place. The contact period, t_c, equals 0.234 s at + 5% BW, 0.236 s at + 10% BW, 0.222 s at + 15% BW, 0.220 s at – 5% BW, 0.218 s at – 10% BW, and 0.219 s at – 15% BW. Other indications as in Fig. 2

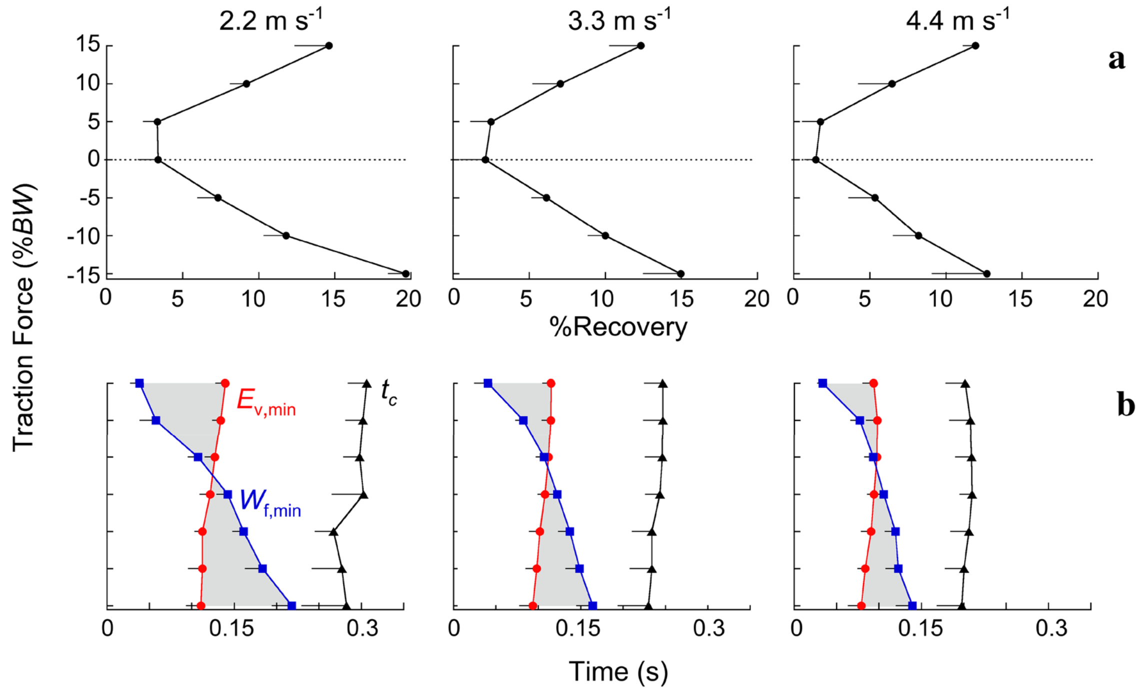


Fig. 6 **a** Energy recovered through an energy exchange between W_f and E_v (%Recovery) as a function of the traction force. **b** The contact period t_c, and the duration between $E_{v,min}$ and $W_{f,min}$ (or vice versa) when running at 2.2, 3.3, and 4.4 m s^{-1}. The grey area corresponds to the period in which an energy transduction is possible (same greyed area as in Fig. 5). Note that, in this figure, the independent variables are presented on the abscissa

Consequently, during the period in which E_v and W_f are out of phase, an exchange between these two curves might occur (Figs. 5 and 6). With an ATF, the W_f-energy lost during the grey zone in Figs. 5 and 6 can be used to increase the height of the CoM, whereas against an HTF, the E_v-energy lost during the grey zone can be used move the CoM forwards. When the applied force becomes greater, the duration between the two minima is lengthened.

The %R expresses the relative amount of energy that could be recovered by an exchange between E_v and W_f, and vice versa. At a given speed, %R increases with the magnitude of the hindering/aiding force (Fig. 6a). When running at 2.2 m s^{-1}, %R reaches a maximum of ~ 20% at − 15% BW and of ~ 16% at + 15% BW. When speed increases, %R at a given traction force is reduced. This might be explained by the fact that the period during which the energy transduction can occur is reduced when speed increases (Fig. 6b). Note also that %R is significantly higher at negative traction forces compared to positive traction forces.

Comparison of running against traction with running on a slope

In this study, we have compared the ratio W_{ext}^{-}/W_{ext}, the average vertical acceleration during t_{ce}, i.e.,$\overline{a}_{v,ce}$ and the ratio t_{brake}/t_{push} between running with/against a traction force and running on a negative/positive slope. These last data were obtained from Dewolf et al. (2016).

As seen in Fig. 7a, the ratio W_{ext}^{-}/W_{ext} presents equivalent values in both conditions. Note that when running unperturbed on the level at a constant average speed, this ratio is equal to 0.5 and does not vary with increasing speed. Downhill/with an ATF, this ratio increases above 0.5 and does not change with speed; on an uphill/against an HTF, the ratio falls below 0.5.

In all conditions, $\overline{a}_{v,ce}$ increases with running speed. As compared to unperturbed running, $\overline{a}_{v,ce}$ while running with an ATF or on a negative slope increases when the magnitude of the traction force/slope increases (Fig. 7b). On the contrary when running with an HTF or on a positive slope, $\overline{a}_{v,ce}$ decreases when the magnitude of the traction force/slope increases.

When the traction is hindering the forward motion of the runner, the t_{brake}/t_{push} ratio decreases similarly when the magnitude of the traction and the slope increases (Fig. 7c). With an ATF or during downhill running, t_{brake}/t_{push} increases with the magnitude of the traction/slope.

Discussion

The mechanism of running on a firm and flat terrain can be compared to a mass mounted on a spring that bounces on the ground. This mechanism is modified in the presence of external factors, such as, for example, the slope (Dewolf et al. 2016) or the nature of the terrain (Lejeune et al. 1998; Ferris et al. 1998; Dewolf et al. 2019). In the present study, we have analysed how a horizontal traction force applied to the trunk of the runner affects the bouncing mechanism of running. Our results show that a horizontal traction force modifies the unbalance between positive and negative work done to sustain the motion of the CoM, the on–off ground asymmetry, the ratio t_{brake}/t_{push}, and the phase shift between the E_v- and E_{kf}-curves. We also showed that, as in walking (Dewolf et al. 2020), some similarities exist between running with/against a traction force and running uphill and downhill.

In the first subsection of the discussion, we will examine how these variables affect the bounce of the spring–mass system during running with a traction force. We will show that these modifications are tuned to limit the increase in the positive or negative muscular power. In a second subsection, these modifications will be compared to the ones observed when running on a slope.

How to limit the increase in power due to the traction force?

In the presence of a horizontal traction force, an imbalance between $W_f{}^+$ and $W_f{}^-$ increases gradually as force increases; whereas $W_v{}^+$ and $W_v{}^-$ remain about equal to the values observed when running without a traction force (Fig. 3). When running against an HTF, the imbalance between $W_f{}^-$ and $W_f{}^+$ is tipped towards $W_f{}^+$. The opposite is observed when running with an ATF. Therefore, the imbalance between $W_{ext}{}^+$ and $W_{ext}{}^-$ is brought on by the imbalances between $W_f{}^+$ and $W_f{}^-$.

The imbalance between positive and negative work done is also accompanied by an imbalance in the duration of the work production to reduce the power necessary to sustain the movement of the CoM (Fig. 5). Indeed, when running against a horizontal traction force, the duration of $W_f{}^+$ is lengthened and that of $W_f{}^-$ is shortened. The contrary is observed when running with ATF: the duration of $W_f{}^-$ is lengthened and that of $W_f{}^+$ is shortened. However, in both situations, the durations of $W_v{}^+$ and $W_v{}^-$ are less affected by the traction.

The changes in the duration of $W_f{}^+$ and of $W_f{}^-$ without changes in the durations of $W_v{}^+$ and $W_v{}^-$ will have two consequences on the positive and negative muscular power ($\dot{W}^+_{ext}$ and $\dot{W}^-_{ext}$). First, the duration of t_{push} with an HTF and of t_{brake} with an ATF will be increased (Fig. 4b) as compared to unperturbed running, with the consequence that the increase in $\dot{W}^+_{ext}$ with an HTF and of $\dot{W}^-_{ext}$ with an ATF will be contained. Second, since the W_f- and E_v-curves are no longer in phase and energy, exchange between these two curves will occur (Fig. 6). However, this energy transduction mechanism saves at best 20% of W_{ext}.

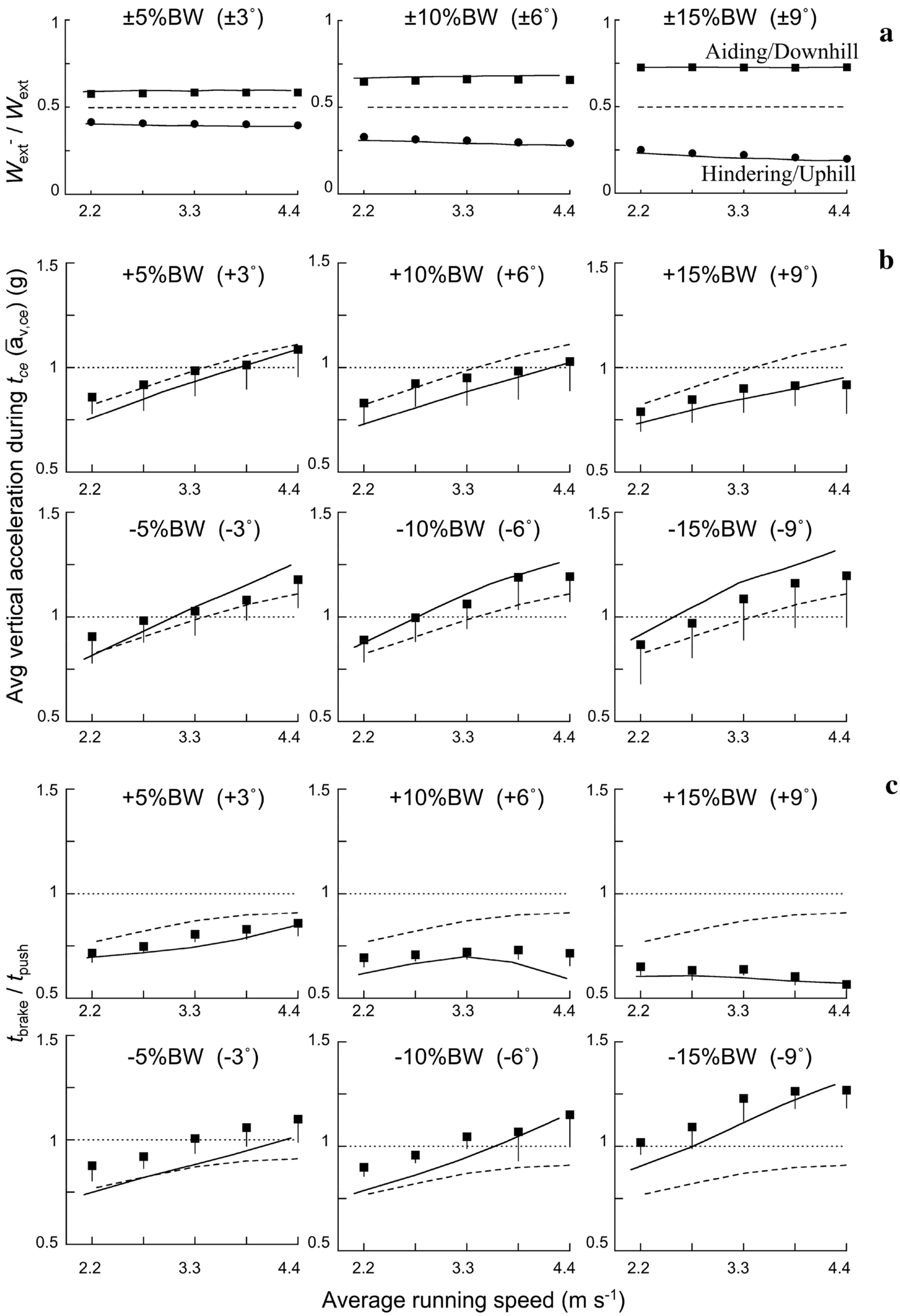
As compared to unperturbed running, t_{ce} is not affected by an HTF, whereas t_{ae} decreases when the HTF increases. This reduction of t_{ae} is due, at least in part, to a reduction of t_a, which occurs for the following reason. When running unperturbed, the fore–aft velocity of the CoM (v_f) remains constant during t_a. On the contrary, when running against an HTF, the traction reduces v_f during t_a. Consequently, the longer the aerial phase, the greater the work required to reaccelerate the CoM ($W_f{}^+$) during contact. In other words, a short t_a reduces $W_f{}^+$. Since at a given speed, t_{ce} does not change and t_{ae} becomes shorter, the step period T is reduced. Consequently, (1) the step remains symmetrical (i.e., $t_{ce} \approx t_{ae}$) at higher speeds than in unperturbed running (Fig. 4) and (2) the step frequency at a given speed is increased, which reduces the $\dot{W}_{ext}$ (Cavagna et al. 1991).

As compared to unperturbed running, both t_{ce} and t_{ae} (and thus T) are not affected by an ATF (Fig. 4) and the on–off ground symmetry is not modified. On the contrary, t_a increases, whereas t_c is reduced. These results are in agreement with those observed during 'unweighted running' (Chang et al. 2001; He et al. 1991). Furthermore, as compared to unperturbed running, $\overline{a}_{v,ce}$ increases with an ATF (Fig. 7b); this is made possible by increased eccentric muscular contractions during landing.

Is running against traction similar to running on a slope?

In 2005, di Prampero et al. hypothesised that if a subject is running at constant speed on an incline, the angle between the runner and the slope is equivalent to the angle formed by a runner tilting forwards while accelerating constantly on the level. If we were to replace this acceleration by a constant force pulling the subject backwards while running at a constant speed on the level, the subject should consequently tilt forwards in a similar way (Fig. 8).

When running at constant speed on a slope, the average fore–aft component of the GRF over a step ($\overline{F}_h$) is nil and its average vertical component ($\overline{F}_v$) is equal to BW. In addition, the average fore–aft component of the velocity of the CoM $\overline{v}_f = v_{belt} \cos \theta$, where θ is the slope of the terrain and $\overline{v}_v = v_{belt} \sin \theta$. Consequently, the average power ($\overline{P}_s$) spent on a slope to maintain the fore-aft ($\overline{P}_f$) and vertical ($\overline{P}_v$) movement of the CoM is given by:


a
±5%BW (±3˚)
±10%BW (±6˚)
±15%BW (±9˚)
Aiding/Downhill
Hindering/Uphill
W_{ext}^{-} / W_{ext}
b
+5%BW (+3˚)
+10%BW (+6˚)
+15%BW (+9˚)
-5%BW (-3˚)
-10%BW (-6˚)
-15%BW (-9˚)
Avg vertical acceleration during t_{ce} ($\bar{a}_{v,ce}$) (g)
c
+5%BW (+3˚)
+10%BW (+6˚)
+15%BW (+9˚)
-5%BW (-3˚)
-10%BW (-6˚)
-15%BW (-9˚)
t_{brake} / t_{push}
Average running speed (m s^{-1})

◂**Fig. 7** Comparisons between data obtained while running unperturbed (dashed lines), on the level against/with a traction force (filled symbols) and on a positive/negative slope (continuous lines). Data on a slope are from Dewolf et al. (2016). **a** Ratio W_{ext}^{-}/W_{ext} when running with an ATF (filled squares) and against an HTF (filled circles). **b** Average vertical acceleration of the CoM during t_{ce} ($\bar{a}_{v,ce}$). When $\bar{a}_{v,ce}$ goes beyond 1 g, step becomes asymmetric (i.e., $t_{ce} < t_{ae}$). **c** Ratio between t_{brake} and t_{push}. If t_{brake}/t_{push} increases above 1, more time is spent braking than accelerating the movement of the CoM. Other indications as in Fig. 4

$$\overline{P}_s = \overline{P}_f + \overline{P}_v = \overline{F}_h\overline{v}_f + \overline{F}_v\overline{v}_v = 0 + BW\overline{v}_f \tan\theta. \quad (12)$$

When running at constant speed with a traction force, $\overline{F}_h$ is equal to the average traction force ($\overline{F}_{tr}$, expressed as a percentage p of BW) and $\overline{F}_v = BW$. The $\overline{v}_f$ represents the average horizontal speed of progression, whereas $\overline{v}_v = 0$, since the subject is running on the level. Consequently, the average power ($\overline{P}_{tr}$) spent to run against/with a traction force is given by:

$$\overline{P}_{tr} = \overline{P}_f + \overline{P}_v = \overline{F}_h\overline{v}_f + \overline{F}_v\overline{v}_v = pBW\overline{v}_f + 0. \quad (13)$$

Since tan (3°) ≈ 0.05, tan (6°) ≈ 0.10, and tan (9°) ≈ 0.15, the average power spent on a ± 3°, ± 6°, and ± 9° slope are roughly equivalent to the power spent with a traction force of ± 5%BW, ± 10%BW, ± 15%BW, respectively.

As compared to running unperturbed, in one case, net $\dot{W}_{ext}$ must be performed to change the potential energy to the CoM, whereas in the other case, net $\dot{W}_{ext}$ must be performed to maintain the fore-aft movement of the CoM. It should be noted that W_{ext}^{+} and W_{ext}^{-} present equivalent values in the present study as those observed by Dewolf et al. (2016) when running on a slope. Therefore, as predicted by Eqs. (12) and (13), the variations brought on vertically by the slope ($W_{v,slope}$) are similar to those brought on horizontally by a traction force ($W_{f,tr}$). As shown in Fig. 7a, the ratio between W_{ext}^{-}/W_{ext} describes this similarity. Note that when running on the level unperturbed, this ratio is equal to 0.5 and does not vary with increasing speed. Downhill/with an ATF, this ratio increases above 0.5 and does not change with speed; on an uphill/against an HTF, the ratio falls below 0.5.

When running with an HTF, $\overline{a}_{v,ce}$ decreases when the magnitude of the traction force increases. A comparable behaviour is observed when running uphill (Dewolf et al. 2016): the on–off ground symmetry is maintained at higher speeds to limit the increase in required force production and so the $\dot{W}_{ext}$. Similarly, as compared to young runners, elderly adults running present an $\overline{a}_{v,ce}$ that is 40% lower (Cavagna et al. 2008b), which can be attributed to a loss of muscular strength with age.

Furthermore, the ratio between concentric and eccentric muscular contractions is similar when running with a traction force and on a slope. The t_{brake}/t_{push} ratio decreases similarly when both the magnitude of the HTF and the positive slope of the terrain increase (Fig. 7c). Likewise, t_{brake}/t_{push} increases when both the magnitude of the ATF and the negative slope of the terrain increase.

Prior to the present study, Chang and Kram (1999) also compared running at 14 km h^{-1} with/against a pulling force to running on a slope. They concluded that although both conditions resemble each other "qualitatively", they are rather different "quantitively". Indeed, they found that when running against a horizontal impeding force, the step frequency does not change, whereas it increases when running on a positive slope (Minetti et al. 1994; Dewolf et al. 2016). Therefore, these authors argued that the internal work required to move the limbs according to the CoM (W_{int}) will not vary against a traction force but will increase with slope. However, in the present study, we observe that the stride frequency increases with the magnitude of the hindering force. An explanation for which Chang and Kram did not observe a significant change in stride frequency can be because they only measured HTFs up to + 6% BW, whereas a significant increase in stride frequency is observed if the HTF is equal or greater than + 10% BW.

In summary, the changes in the bouncing mechanism observed when running with a hindering/aiding force are similar to the ones observed when running on the slope. In both cases, the duration of positive/negative power production is lengthened to limit this increase in power. Furthermore, the additional work done is limited by transforming kinetic into potential energy and vice versa. This energy transduction allows us to reduce the additional work by 15–20%, depending on the magnitude of traction force or on the inclination of the terrain. In a near future, it would be interesting to extend the comparison to an accelerating/decelerating situation and to analyse—in a wind tunnel for example—if running against/with the wind is comparable to running with a hindering/aiding force.

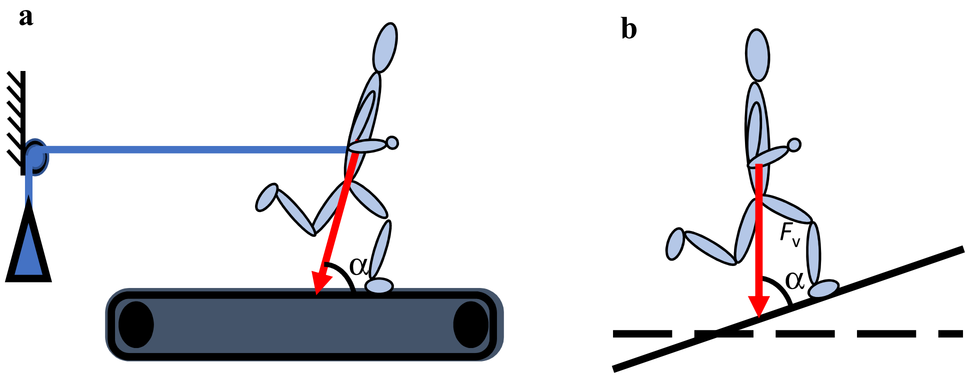


Fig. 8 Schema illustrating that the angle between a subject and level ground when running against a traction force (**a**) is equivalent to the angle between the subject and the slope when running uphill (**b**). Modified from di Prampero et al. (2005)

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Compliance with ethical standards

Conflict of interests The authors declare no competing or financial interests.

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