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Energy exchange during running with an aiding and hindering force

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1. Introduction

When walking, the kinetic energy of the centre of mass of the body (CoM) due its forward movement (E_{kf}) and the mechanical energy due to its vertical movement (E_v) are out of phase, allowing energy exchange between the E_{kf} and E_v (Cavagna et al. 1976). On the contrary, in running, the time curves of E_{kf} and E_v are in phase. Consequently, the trajectory of the CoM reaches its lowest point close to the middle of the contact phase, when its forward velocity is minimal. In this case, the energy exchange between E_{kf} and E_v is almost nil.

It has recently been shown that during running on a slope, some energy (about 20% of the external work necessary to move the CoM relative to the environment, W_{ext}) can be recovered through exchange between E_{kf} and E_v (Dewolf et al. 2016). This phenomenon occurs because on a slope, there is an imbalance between the positive and negative work performed. Consequently, in order to contain the increase in the positive (uphill) or negative (downhill) power necessary to change the height of the CoM, the time during which E_v increases/decreases is lengthened, whereas the time during which the CoM is accelerated/decelerated forwards does not change. Thus, when slope and speed increase the minimum of E_v takes place prior/after the minimum of E_{kf} , causing a period during which an energy exchange between E_{kf} and E_v occurs.

When moving with a hindering/aiding horizontal force, muscles need to produce work not only to maintain E_{kf} , but also to counteract this horizontal force (W_{tr}). In this way, the work done to sustain the movement of the CoM in the fore-aft direction (E_f) is equal to the sum of the E_{kf} and W_{tr} -time curves. The present study is intended to investigate the shift between E_f and

E_v , when moving against/with a traction force pulling the participant horizontally. We hypothesise that when running against/with a traction force, in order to reduce the power necessary for propulsion/braking, the duration of the positive/negative work phase needed to accelerate/decelerate the CoM will be lengthened, whereas the duration of the positive/negative work phase to increase the height of the CoM will be less affected by the traction. Because of this imbalance, the fluctuations between E_f and E_v will no longer be in phase and we expect that an energy exchange will occur between E_f and E_v (Cavagna et al. 2008). These modifications due to the hindering/aiding force will be compared to those observed when running uphill/downhill (Dewolf et al. 2016).

2. Methods

Eight male participants (age: 20.9 ± 1.6 years, mass: 72.8 ± 5.6 kg, height: 1.8 ± 0.1 m, mean $\pm$ sd) ran at 3.33 m s^{-1} on an instrumented treadmill (h/p/ CosmosStellar, Germany) while being pulled forwards or backwards by a traction force representing 0%, $\pm 5\%$, $\pm 10\%$ and $\pm 15\%$ of their body weight (BW). All participants gave informed consent.

An upper body harness was attached to a weight via an elastic rope and a pulley as in Asmussen and Bonde-Petersen (1974). Due to friction and inertia, the traction force varied within $\pm 0.5\%$ of BW during the step.

The three components of the ground reaction force (lateral F_x , vertical F_z and fore-aft F_y) and the traction force (F_{tr}) were measured every 1 ms by a 16 bits A/D convertor. The change in the traction force due to the vertical oscillation of the fixation point on the harness is in the order of 0.1% and was therefore neglected. From these data, the acceleration, velocity and displacement of the CoM were computed (Dewolf et al. 2016). Then, E_{kf} and E_v were calculated as:

$$E_v = m g S_v + \frac{1}{2} m V_v^2 \quad (1)$$

$$E_{kf} = \frac{1}{2} m V_f^2 \quad (2)$$

where m is the body mass, V_v and V_f are the vertical and horizontal components of the velocity of the CoM and S_v is its vertical displacement. The work done against the traction (W_{tr}) and E_f were computed as

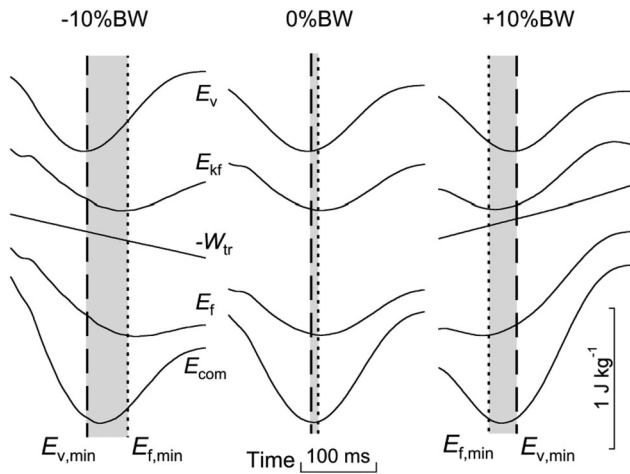


Figure 1. Typical mass specific energy-time curves of the COM during the contact phase of one participant running at 3.33 m s^{-1} without (0% BW) and with a traction force, hindering (+10% BW) or aiding (-10% BW) the runner. The dashed and dotted lines represent the minimum of the E_v -curve ($E_{v,min}$) and of the E_f -curve ($E_{f,min}$), respectively. The grey zone corresponds to the period during which an energy exchange between E_v and E_f occurs. For other symbols, see text.

$$W_{tr} = \int W_{tr} V_b dt \quad (3)$$

$$E_f = E_{kf} + W_{tr} \quad (4)$$

where V_b is the average velocity of the treadmill belt over the step analysed. The total energy of the CoM (E_{com}) was computed as:

$$E_{com} = E_v + E_f \quad (5)$$

Energy exchange (%R) was quantified as (Cavagna et al. 2008):

$$\%R = \frac{W_f^+ + |W_f^-| + W_v^+ + |W_v^-| - (W_{com}^+ + |W_{com}^-|)}{W_f^+ + |W_f^-| + W_v^+ + |W_v^-|} \quad (6)$$

where W_f^+ , W_f^- , W_v^+ , W_v^- are the positive and negative work done to sustain the movements of the CoM in the fore-aft (subscript f) and vertical (subscript v) directions and W_{com}^+ , W_{com}^- are the positive and negative muscular work actually done to sustain the movement of the CoM relative to the environment.

3. Results and discussion

When a hindering/aiding force is applied to the body, the bouncing mechanism of running is modified (Figure 1). When running without a traction force, the E_f and E_v curves are in phase. With a hindering horizontal force, $E_{f,min}$ precedes $E_{v,min}$ whereas with an aiding force $E_{f,min}$ follows $E_{v,min}$. In the first case, the E_v -energy lost during the grey zone of Figure 1 can be used to increase the kinetic

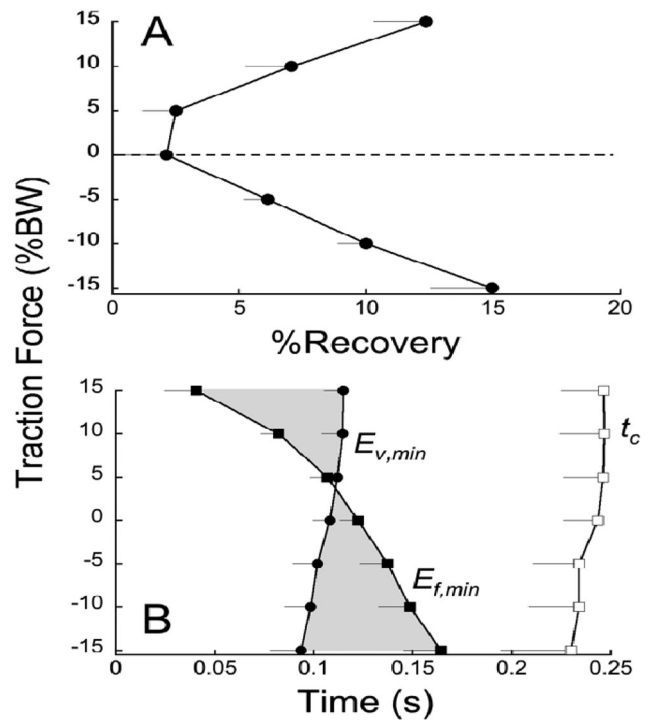


Figure 2. Energy exchange (%R) (A) and duration of the contact phase (t_c) as a function of the traction force when running at 3.33 m s^{-1} . In panel B, the grey zone corresponds to the time shift between $E_{v,min}$ and $E_{f,min}$ where an energy transfer is possible. Symbols and bars represent the grand mean and standard deviations, respectively (when bars extend from the mean) of all participants ($n = 8$).

energy of the CoM (E_{kf}) or to do work against the traction force (W_{tr}). In the second case, the E_f -energy lost during the grey zone can be used to increase the height of the CoM (E_v).

When the applied force becomes greater, the duration between the two minima is lengthened (Figure 2B). Consequently, the possibility of energy exchange between E_f and E_v (and *vice versa*) increases with the traction up to 10% with a hindering force and to 15% with an aiding force (Fig. 2A).

The changes in the bouncing mechanism observed when running with a hindering/aiding force (like the wind for example) are similar to the ones observed when running on 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 exchange allows to reduce the additional work by 1520%, depending on the magnitude of traction force or on the inclination of the terrain.

4. Conclusion and perspectives

When a horizontal traction force is applied to the body, the bouncing mechanism of running is modified. These

primary results are obtained at an intermediate speed of 3.33 m s^{-1} . In future experiments, the effect of speed on these modifications should also be analysed.

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KEYWORDS Biomechanics; running; bouncing mechanism

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