

## RESEARCH ARTICLE

# The rebound of the body during uphill and downhill running at different speeds

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## ABSTRACT

When running on the level, muscles perform as much positive as negative external work. On a slope, the external positive and negative work performed are not equal. The present study analysed how the ratio between positive and negative work modifies the bouncing mechanism of running. Our goals are to: (1) identify the changes in motion of the centre of mass of the body associated with the slope of the terrain and the speed of progression, (2) study the effect of these changes on the storage and release of elastic energy during contact and (3) propose a model that predicts the change in the bouncing mechanism with slope and speed. Therefore, the ground reaction forces were measured on 10 subjects running on an instrumented treadmill at different slopes (from  $-9$  to  $+9$  deg) and different speeds (between  $2.2$  and  $5.6$  m s<sup>-1</sup>). The movements of the centre of mass of the body and its external mechanical energy were then evaluated. Our results suggest that the increase in the muscular power is contained (1) on a positive slope, by decreasing the step period and the downward movements of the body, and by increasing the duration of the push, and (2) on a negative slope, by increasing the step period and the duration of the brake, and by decreasing the upward movement of the body. Finally, the spring-mass model of running was adapted to take into account the energy added or dissipated each step on a slope.

**KEY WORDS:** Locomotion, Running, Bouncing mechanism, Slope, External work

## INTRODUCTION

When running on the level at a constant average speed, the mechanical energy of the centre of mass of the body (COM) oscillates throughout the step like a spring-mass system bouncing on the ground (Cavagna et al., 1976). During the rebound of the body, the muscle–tendon units (MTU) of the supporting lower limb undergo a stretch–shortening cycle during which part of the mechanical energy of the COM is absorbed during the negative work phase to be restored during the next positive work phase (Cavagna et al., 1988).

When running on the level, the upward and downward movements of the COM are equal, and the positive and negative work done each step to sustain its movements relative to the surroundings are equal (i.e.  $W_{\text{ext}}^+ = W_{\text{ext}}^-$ ). When running on a slope,

muscles are compelled to produce or dissipate energy to increase or decrease the potential energy of the COM (DeVita et al., 2008). In this case, the spring-mass model is not suitable anymore because the ratio between positive and negative work increases or decreases with the slope of the terrain (Minetti et al., 1994). Several aspects of the mechanics of human running uphill and downhill have been studied these last decades: e.g. the muscular work done, the energy consumed and the muscular efficiency at different slopes (Minetti et al., 1994), the net muscular moment and power at the hip, knee and ankle during uphill running (Roberts and Belliveau, 2005), and the possible elastic energy storage and recovery in the arch and Achilles' tendon while running uphill and downhill (Snyder et al., 2012).

To our knowledge, the change in the bouncing mechanism while running on a slope at different speeds has never been analysed. Indeed, this mechanism will be affected by the ratio between positive and negative work. Between  $2.2$  and  $3.3$  m s<sup>-1</sup>, this ratio changes with the slope of the terrain, but not with the speed of progression (Minetti et al., 1994). However, to the best of our knowledge, this ratio has never been measured while running on a slope at higher speeds.

To analyse the bouncing mechanism, we have measured the three components of the ground reaction force (GRF) of 10 subjects running on an inclined treadmill (from  $-9$  to  $+9$  deg, in  $3$  deg increments) at 10 different speeds (from  $2.2$  to  $5.6$  m s<sup>-1</sup>). From these curves, we have analysed (1) the different periods of the running steps, (2) the vertical movements of the COM and (3) the energy fluctuations of the COM in order to understand how the bouncing mechanism of running deviates from the spring-mass model with slope and speed. We believe that three aspects of this mechanism will be affected.

First, from a mechanical point of view, a spring-mass system bouncing vertically on the ground 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). This is true whatever the slope; indeed, when running in steady state, the average vertical velocity of the COM ( $\bar{V}_v$ ) does not change from one step to the next. Consequently, the average vertical acceleration of the COM  $\bar{a}_v = 0$  and the average force  $\bar{F}_v = \text{BW}$ . The step period ( $T$ ) can thus be divided into two parts: the first during which  $F_v > \text{BW}$  ( $t_{\text{ce}}$ ), taking place during the contact of the foot on the ground, and the second during which  $F_v \leq \text{BW}$  ( $t_{\text{ae}}$ ), taking place during both ground contact and the aerial phase. The period  $t_{\text{ce}}$  corresponds to the half period of the oscillation of the bouncing system. During  $t_{\text{ae}}$ , the bouncing model is not valid when the body leaves the ground.

When running on a flat terrain at speeds up to  $\sim 3.1$  m s<sup>-1</sup>,  $t_{\text{ce}} \approx t_{\text{ae}}$  (symmetric step). As speed increases above  $3.1$  m s<sup>-1</sup>,  $t_{\text{ae}}$  becomes progressively greater than  $t_{\text{ce}}$  (asymmetric step). This asymmetry arises from the fact that, when speed increases, the average vertical acceleration during  $t_{\text{ce}}$  (i.e.  $\bar{a}_{v,\text{ce}}$ ) becomes greater than the acceleration of gravity ( $g$ ) whereas during  $t_{\text{ae}}$ ,  $\bar{a}_{v,\text{ae}}$  cannot exceed

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**List of symbols and abbreviations**

$a_v$	vertical acceleration of the COM
$\bar{a}_v$	average vertical acceleration of the COM over a complete number of steps
$\bar{a}_{v,ce}, \bar{a}_{v,ae}$	average vertical acceleration of the COM during $t_{ce}$ and $t_{ae}$
$b$	constant depending of the initial conditions in the spring-actuator-mass model
BW	body weight
$c$	actuator coefficient in the spring-actuator-mass model
COM	centre of mass of the whole body
$E_{ext}$	mechanical energy of the COM
$E_f, E_l, E_v$	energy due to the fore-aft, lateral and vertical movement of the COM
$E_{f,min}, E_{v,min}$	minimum of the $E_f$ - and $E_v$ -time curves
$F_f, F_l, F_v$	fore-aft, lateral and vertical components of the GRF
$F_p, F_n$	component of the GRF parallel and normal to the treadmill surface
$\bar{F}_v$	average vertical GRF over a complete number of steps
GRF	ground reaction force
$k$	overall vertical stiffness of the leg-spring in the spring-actuator-mass model
$L$	step length
MTU	muscle-tendon unit
RMSE	root mean square error
$S$	vertical displacement of the COM
$S^+, S^-$	upward and downward displacement of the COM over a step
$S_a^+, S_a^-$	upward and downward displacement of the COM taking place during $t_a$
$S_c^+, S_c^-$	upward and downward displacement of the COM taking place during $t_c$
$S_{min}$	minimum vertical displacement necessary to overcome the slope each step
$T$	step period
$t_c, t_a$	contact time and aerial time
$t_{ce}, t_{ae}$	effective contact time and effective aerial time
$t_{push}, t_{brake}$	duration of the positive and of the negative work phase
$V_{belt}, \bar{V}_{belt}$	instantaneous and average velocity of the belt
$V_f, \bar{V}_f$	instantaneous and average fore-aft velocity of the COM relative to the belt
$V_l$	instantaneous lateral velocity of the COM
$V_v, \bar{V}_v$	instantaneous and average vertical velocity of the COM relative to the belt
$W_{ext}^+, W_{ext}^-$	positive and negative external work done to sustain the mechanical energy changes of the COM relative to the surroundings
$W_{ext}$	sum of $W_{ext}^+$ and the absolute value of $W_{ext}^-$
$W_f^+, W_f^-$	positive and negative work done to sustain the fore-aft movement of the COM
$W_l^+, W_l^-$	positive and negative work done to sustain the lateral movement of the COM
$W_v^+, W_v^-$	positive and negative work done to sustain the vertical movement of the COM
$\dot{W}_f, \dot{W}_l, \dot{W}_v$	power spent to move the COM in the fore-aft, lateral and vertical directions
%R	percentage of energy recovered through the transduction between $E_v$ and $E_f$
$\theta$	slope of the treadmill

1 **g**. Consequently, a longer  $t_{ae}$  is necessary to dissipate and restore the momentum lost and gained during  $t_{ce}$ . At a given speed for a given  $t_{ce}$ , the asymmetric step requires a greater  $\bar{a}_{v,ce}$ ; however, the increase in the step period due to a longer  $t_{ae}$  results in a smaller internal power necessary to reset the limbs at each step (Cavagna et al., 1988).

When running on a positive slope, muscles are performing more positive than negative work. We expect that in order to contain the increase in muscular forces during  $t_{ce}$ , the step remains symmetric

above  $3.1 \text{ m s}^{-1}$  and  $T$  becomes shorter than during running on the level. In contrast, when running on a negative slope, muscles are performing more negative work. Because muscles are able to develop higher forces during eccentric contractions, we expect that  $T$  is tuned to contain the internal power, rather than the force during  $t_{ce}$ . Consequently,  $T$  should become longer than during running on the level and the step should become asymmetric below  $3.1 \text{ m s}^{-1}$ .

Second, when running on a flat terrain, the momentums lost and gained over a step are equal, and  $\bar{V}_v=0$ . Consequently, the upwards and downwards vertical displacements of the COM ( $S^+$  and  $S^-$ ) are equal. On the contrary, when running on a slope,  $\bar{V}_v \neq 0$  and  $S^+ \neq S^-$ . We expect that the dissimilarity between  $S^+$  and  $S^-$  will be the main factor affecting the bouncing mechanism. We also expect that  $S^-$  in uphill and  $S^+$  in downhill running will progressively disappear and with it the amount of energy that can potentially be stored in the MTU.

Third, on a flat terrain, the energy that is due to the vertical movements of the COM ( $E_v$ ) and the energy that is due to its horizontal movements ( $E_f$ ) are fluctuating in phase (Cavagna et al., 1976), and the negative and positive work done are approximately equal:  $\Delta^+ E_f \approx \Delta^- E_f$  and  $\Delta^+ E_v \approx \Delta^- E_v$ . However, when running on a slope,  $\Delta^+ E_f \approx \Delta^- E_f$  but  $\Delta^+ E_v \neq \Delta^- E_v$ . We expect that (1) because of this imbalance, the fluctuations of  $E_f$  and  $E_v$  are no longer in phase and, consequently, (2) an energy exchange occurs between these two curves. Therefore, we have evaluated the duration of the positive and negative work phases and the energy transduction between  $E_f$  and  $E_v$  during the period of contact  $t_c$  (Cavagna et al., 2008a).

We hypothesize that the three aspects described here above will jeopardize the bouncing mechanism of running and in turn, the possibility to store and release elastic energy into the elastic structures of the lower limb. However, we also hypothesize that the disappearance of this mechanism is intended to restrain the increase in  $W_{ext}^+$  or  $W_{ext}^-$  that is due to slope.

Finally, we propose a model that describes the vertical oscillations of the COM during  $t_{ce}$  while running on a slope. The aim of this model is to understand how all of the lower-limb muscles are tuned to generate the basic oscillation of the bouncing system. The spring-mass system bouncing on the ground that models running on the level (Blickhan, 1989; Cavagna et al., 1988) cannot describe running on a slope because energy must be added or dissipated. Therefore, we have incorporated an actuator in the spring-mass model that will generate a force proportional to  $V_v$  and produce or absorb energy during contact.

**MATERIALS AND METHODS****Subject and experimental procedure**

Ten recreational runners (three females and seven males) participated in the study (age:  $31.8 \pm 8.3$  years, mass:  $68.8 \pm 10.2$  kg, height:  $1.78 \pm 0.07$  m, mean  $\pm$  s.d.). Informed written consent was obtained from each subject. The studies followed the guidelines of the Declaration of Helsinki, and the procedures were approved by the Ethics Committee of the Université catholique de Louvain.

Subjects ran on an instrumented treadmill at seven different inclinations: 0,  $\pm 3$ ,  $\pm 6$  and  $\pm 9$  deg. To neutralize the effect of learning and muscle fatigue, half of the subjects started with an inclination of 0 deg that was increased and the other half with an inclination of 9 deg that was decreased. At each slope, subjects ran at 10 speeds presented in a different order (8, 10, 11, 12, 13, 14, 15, 16, 18 and  $20 \text{ km h}^{-1}$ , corresponding to 2.22, 2.78, 3.06, 3.33, 3.61, 3.89, 4.17, 4.44, 5.00 and  $5.56 \text{ m s}^{-1}$ , respectively). Note that

for downhill running, the speed of the belt was limited by the manufacturer to  $5.0 \text{ m s}^{-1}$ . At each slope, half the subjects started with the belt turning forwards to simulate uphill running and the other half with the belt turning backwards to simulate downhill running.

Data were recorded during a period of 3–10 s, depending of the speed and the inclination of the treadmill. Between 6 and 36 steps per trial were recorded; a total of 15,760 steps were analysed. On a +6 deg slope, one subject could not run at  $5.6 \text{ m s}^{-1}$ , and on a +9 deg slope, one subject could not run at  $5.0 \text{ m s}^{-1}$  and three could not run at  $5.6 \text{ m s}^{-1}$ .

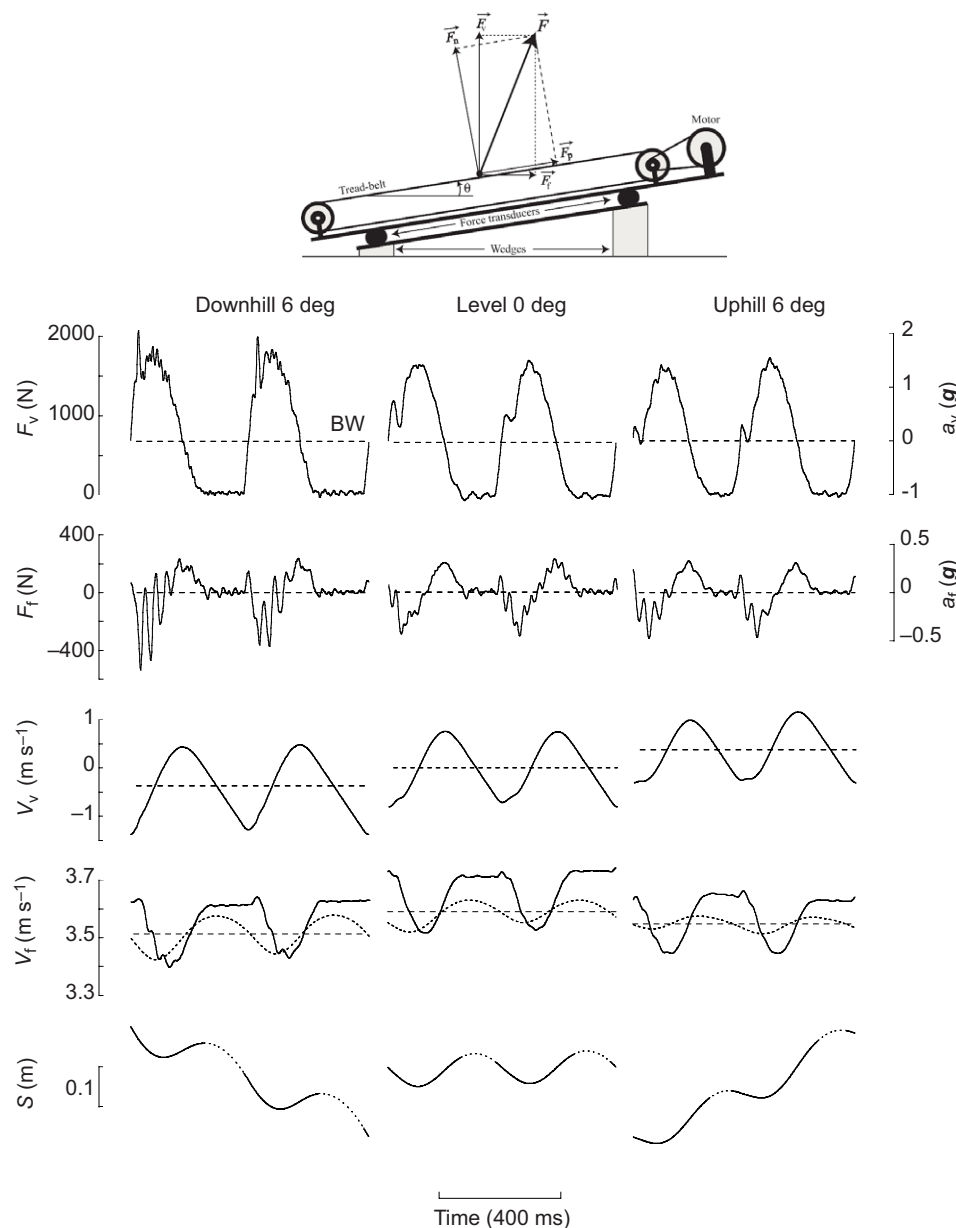
### Experimental setup and data analysis

The instrumented treadmill (Fig. 1) consisted of a modified commercial treadmill (h/p/Comos-Stellar, Germany, belt surface:  $1.6 \times 0.65 \text{ m}$ , mass:  $\sim 240 \text{ kg}$ ) combined with four force transducers (Arsalis, Belgium), designed on the principle described by Heglund (1981). 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):  $F_p$ , the component parallel to the long axis of the tread surface;  $F_n$ , the component normal to the tread surface; and  $F_l$ , the component in the lateral direction. The lowest frequency mode of vibration was  $>41 \text{ Hz}$  for  $F_p$ ,  $47 \text{ Hz}$  for  $F_n$  and  $27 \text{ Hz}$  for  $F_l$ . The non-linearity was  $<1\%$  of full scale, and the crosstalk  $<1\%$ . The fore-aft ( $F_f$ ) and vertical ( $F_v$ ) components of GRF were then computed as:

$$\begin{pmatrix} F_f & F_v \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} F_p \\ F_n \end{pmatrix}, \quad (1)$$

where  $\theta$  is the angle between horizontal and the tread surface. The electrical motor was instrumented with an optical angle encoder to measure the speed of the belt ( $V_{\text{belt}}$ ). The average speed of the belt over a stride ( $\bar{V}_{\text{belt}}$ ) differed by  $2.8 \pm 1.4\%$  (mean  $\pm$  s.d.) from the chosen speed and the instantaneous  $V_{\text{belt}}$  did not change by more than  $5\%$  of  $\bar{V}_{\text{belt}}$ .



**Fig. 1. Schema of the instrumented treadmill (top) and typical time traces of a subject running at  $\sim 3.6 \text{ m s}^{-1}$  on a  $-6 \text{ deg}$  slope (left column), on the level (middle column) and on a  $+6 \text{ deg}$  slope (right column).** The schema at the top of the figure represents the instrumented treadmill. The whole body of the treadmill (including the motor) is mounted on four strain-gauge transducers attached to wedges.  $F_p$  is the component parallel to the long axis of the treadmill surface,  $F_n$  the component normal to the tread surface and  $F_l$  the component in the lateral direction (not represented here).  $\theta$  is the angle between horizontal and the tread surface. The fore-aft ( $F_f$ ) and vertical ( $F_v$ ) components of GRF are computed using Eqn 1. Traces from top to bottom. First and second row, left scale: vertical  $F_v$  and horizontal  $F_f$  components of the ground reaction force exerted by the treadmill under the foot; right scale: acceleration of the COM:  $a_v = (F_v - BW)/m$  and  $a_f = F_f/m$ , where BW is the body weight and  $m$  the body mass. Third row: vertical velocity of the COM,  $V_v$ , relative to a referential attached to the treadmill belt. The horizontal dashed line represents the average vertical velocity of the COM over the stride ( $\bar{V}_v = \bar{V}_{\text{belt}} \sin \theta$ ). Fourth row:  $V_f$  is the fore-aft velocity of the COM. The dashed curve represents the instantaneous velocity of the belt in the fore-aft direction ( $-V_{\text{belt}} \cos \theta$ ). The horizontal dashed line represents the average fore-aft velocity of the COM over the stride ( $\bar{V}_f = \bar{V}_{\text{belt}} \cos \theta$ ). Fifth row: vertical displacement of the centre of mass  $S$  divided into contact phase (continuous line) and aerial phase (dotted line). Tracings were recorded on a subject of height  $1.83 \text{ m}$ , body mass  $68.4 \text{ kg}$  and age 24 years.

The treadmill contained its own signal conditioning system: the GRF signals were amplified, low-pass filtered (4-pole Bessel filter with a  $-3$  dB cut-off frequency at 200 Hz) and digitized by a 16-bit analog-to-digital converter at 1000 Hz. This system was connected to a PC via ethernet using TCP/IP (Genin et al., 2010). Acquisition and data processing were performed using custom-built software (LABVIEW 2010, National Instruments, Austin, TX, USA, and MATLAB 2013, MathWorks, Natick, MA, USA).

### Division of the step

Steps were divided according to the  $F_v$ -time curves (Fig. 1): a step started and ended when  $F_v$  became greater than BW. The effective contact time ( $t_{ce}$ ) was the period during which  $F_v \geq BW$ , and the effective aerial time ( $t_{ae}$ ) was the period during which  $F_v < BW$  (Cavagna et al., 1988). The time of contact ( $t_c$ ) was the period during which  $F_v > 10$  N, and the aerial phase ( $t_a$ ) was the period during which  $F_v \leq 10$  N. The step duration was then calculated as  $T = t_{ce} + t_{ae}$ .

### Measurement of the acceleration, velocity and vertical displacement of the COM

The acceleration ( $a$ ), velocity ( $V$ ) and displacement ( $S$ ) of the COM and the external work done ( $W_{ext}$ ) were computed from the GRF using a method similar to that of Gosseye et al. (2010). Therefore, this method is only explained in brief.

These computations were done over strides (i.e. two steps, starting on the right foot). The fore-aft, lateral and vertical accelerations of the COM relative to the reference frame of the laboratory were calculated by dividing  $F_f$ ,  $F_l$  and  $F_v - \bar{F}_v$  by the body mass  $m$  (where  $\bar{F}_v$  is the average vertical force over a stride). In theory,  $\bar{F}_v = BW$  (as explained in the Introduction); therefore, strides were analysed only if  $\bar{F}_v$  was within 5% of BW.

The time curves of the three components of  $a$  were integrated numerically to determine the fore-aft ( $V_f$ ) lateral ( $V_l$ ) and vertical ( $V_v$ ) velocity of the COM, plus an integration constant, which was set on the assumption that the average velocity of the COM over a

stride was equal to  $\bar{V}_{belt} \cos \theta$  for  $V_f$ , to zero for  $V_l$  and  $\bar{V}_{belt} \sin \theta$  for  $V_v$ .

The vertical displacement of the COM ( $S$ ) was then computed by time integration of  $V_v$ . The upward and downward displacements of the COM were divided according to  $t_c$  ( $S_c^+$  and  $S_c^-$ ) and  $t_a$  ( $S_a^+$  and  $S_a^-$ ). The minimum vertical displacement ( $S_{min}$ ) necessary to overcome the slope of the terrain each step can be computed by  $S_{min} = \bar{V}_f T \sin \theta$ , where  $\bar{V}_f$  is the average running speed over the step and  $\bar{V}_f T$  is the step length.

### Measurement of the positive and negative external work

The external work ( $W_{ext}$ ) is the work necessary to move the COM relative to the surroundings plus the work done on or by the environment (Willems et al., 1995). It was measured from the work done by the GRF (Gosseye et al., 2010).

The power spent to move the COM in the fore-aft ( $\dot{W}_f$ ), lateral ( $\dot{W}_l$ ) and vertical ( $\dot{W}_v$ ) directions was computed, respectively, by:

$$\dot{W}_f = F_f V_f, \quad \dot{W}_l = F_l V_l \quad \text{and} \quad \dot{W}_v = F_v V_v. \quad (2)$$

In the fore-aft and vertical directions, the power spent by the subject on the belt or by the belt on the subject can be computed, respectively, by:

$$-F_f v \cos \theta \quad \text{and} \quad -F_v v \sin \theta, \quad (3)$$

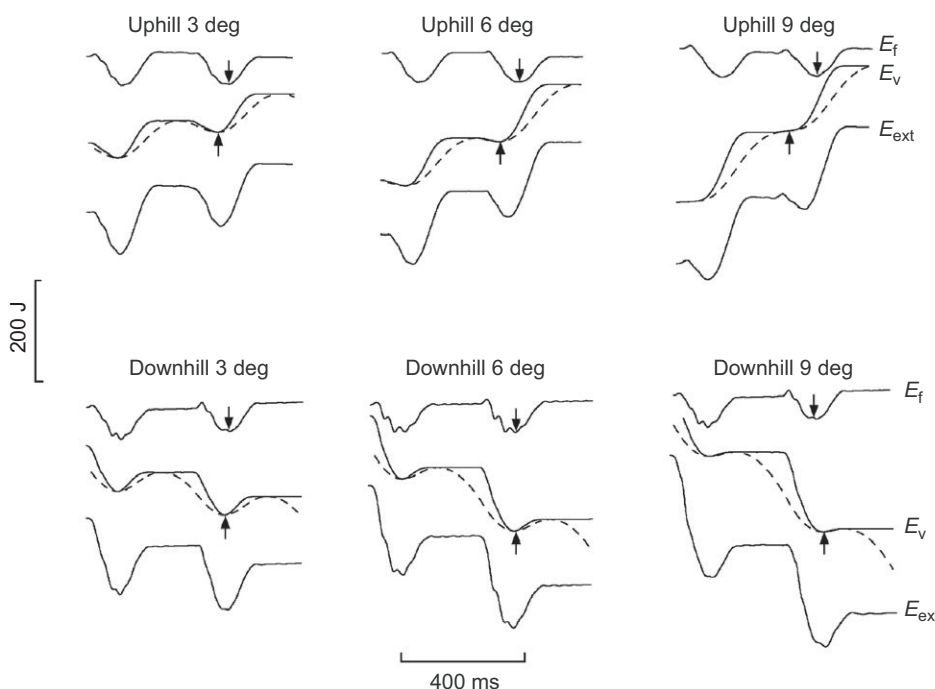
where  $v = V_{belt} - \bar{V}_{belt}$  represents the variation of  $V_{belt}$  around  $\bar{V}_{belt}$ . Because these terms represented less than 3% of  $W_{ext}$ , they were neglected in this study.

The energies ( $E_f$ ,  $E_l$  and  $E_v$ ) that are due, respectively, to the fore-aft, lateral and vertical movements of the COM were computed by:

$$E_f = \int \dot{W}_f dt, \quad E_l = \int \dot{W}_l dt \quad \text{and} \quad E_v = \int \dot{W}_v dt, \quad (4)$$

and the total energy of the COM ( $E_{ext}$ ) by:

$$E_{ext} = \int (\dot{W}_f + \dot{W}_l + \dot{W}_v) dt. \quad (5)$$



**Fig. 2. Energy changes of the COM during a running stride.** Mechanical energy–time curves of the COM during a stride on different slopes, while running at  $\sim 4.2 \text{ m s}^{-1}$ . In each panel, the upper curve ( $E_f$ ) refers to the kinetic energy that is due to the forward motion of the COM, the middle curve ( $E_v$ ) to the sum of the gravitational potential energy (interrupted line) and the kinetic energy that are due to the vertical motion of the COM, and the bottom curve ( $E_{ext} = E_f + E_v$ ) to the total energy of the COM. The arrows pointing downwards indicate the minimum of  $E_f$  and the arrows pointing upwards the minimum of  $E_v$  during the contact phase of the second step. The horizontal segments of the energy curves correspond to the aerial phase. Tracings are from the same subject as in Fig. 1.



The positive and negative work over one step ( $W_f^+$ ,  $W_1^+$ ,  $W_v^+$ ,  $W_{\text{ext}}^+$  and  $W_f^-$ ,  $W_1^-$ ,  $W_v^-$ ,  $W_{\text{ext}}^-$ ) were computed as the sum of the positive and negative increments of the  $E_f$ ,  $E_1$ ,  $E_v$  and  $E_{\text{ext}}$  curves, respectively (Fig. 2). Because  $W_1$  represents less than 1.5% of  $W_{\text{ext}}$ , it is not presented separately in the results. The work per step was computed as the work over the stride divided by two.

### Energy transduction between $E_f$ and $E_v$

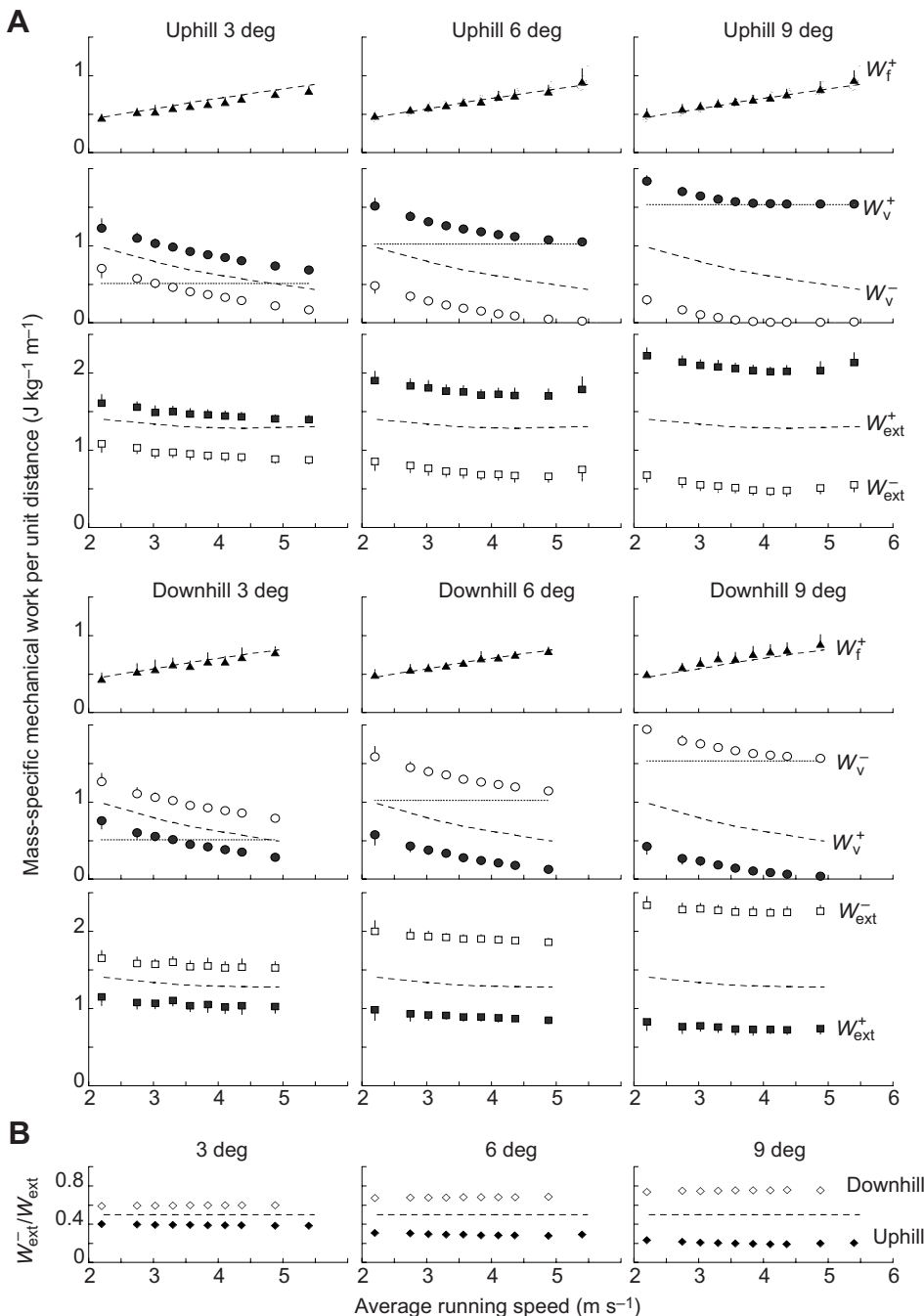
When running on the level, the  $E_f$  and  $E_v$  curves are in phase (Cavagna et al., 1976). However, when running on a slope, these curves could shift one relative to the other, allowing energy transduction between  $E_f$  and  $E_v$  (Fig. 2). The amount of energy recovered (%R) over the contact phase was computed as (Cavagna

et al., 2008a):

$$\%R = 100 \frac{W_f^+ + |W_f^-| + W_v^+ + |W_v^-| + W_1^+ + |W_1^-| - (W_{\text{ext}}^+ + |W_{\text{ext}}^-|)}{W_f^+ + |W_f^-| + W_v^+ + |W_v^-| + W_1^+ + |W_1^-|} \quad (6)$$

### Modelling the vertical movement of the body bouncing system of running

When running on the level, the vertical movement of the COM during  $t_{\text{ce}}$  can be compared with the movement of a spring-mass system bouncing vertically (Blickhan, 1989; Cavagna et al., 1988).



**Fig. 3. Mass-specific external work per unit distance as a function of speed at each slope.** (A) At each slope, the mass-specific positive (closed symbols, superscript +) and negative (open symbols, superscript -) mechanical work done each step is given as a function of running speed.  $W_f$  is the work done to accelerate or decelerate the COM (in this case,  $W_f^+ = W_f^-$ ),  $W_v$  is the work to raise or lower the COM and  $W_{\text{ext}}$  is the muscular work actually done to sustain the movements of the COM relative to the surroundings. Symbols and bars represent the grand mean of the subjects ( $n=10$ , except for +6 deg at  $5.6 \text{ m s}^{-1}$  and +9 deg at  $5.0 \text{ m s}^{-1}$  where  $n=9$ , and +9 deg at  $5.6 \text{ m s}^{-1}$  where  $n=7$ ) and the standard deviations (when the length of the bar exceeds the size of the symbol). In the middle row, the horizontal continuous lines represent the minimum work done to overcome the slope and the dashed lines represent the work done during running on the level; these last lines were drawn through the experimental data (weighted mean, Kaleidagraph 4.5). (B)  $W_{\text{ext}}^-/W_{\text{ext}}^+$  as a function of speed. The open diamonds indicate negative slopes whereas the closed diamonds indicate positive slopes.

In this case, the balance of force is given by:

$$F_v - BW = kS, \quad (7)$$

where  $k$  is the overall stiffness generated by the lower-limb muscles. To describe the vertical movement of the COM during running on a slope, Eqn 7 was implemented by incorporating an actuator parallel to the spring. This actuator generates a force proportional to the magnitude of  $V_v$ :

$$F_v - BW = b + kS + cV_v, \quad (8)$$

where  $b$  is a constant depending on the vertical velocity of the COM at touch down and  $c$  is the actuator coefficient. The coefficient  $c$  is positive when running uphill and negative when running downhill. In this way, the power developed by the actuator force ( $cV_v^2$ ) is positive in uphill running, showing that the actuator works like a motor giving energy to the body, and negative in downhill running, showing that the actuator works like a damper absorbing energy (see insets in Fig. 7A).

At each instant  $i$  of  $t_{ce}$  (which represents the half-period of the oscillation of the system), the vertical acceleration ( $a_v$ ) of the mass  $m$

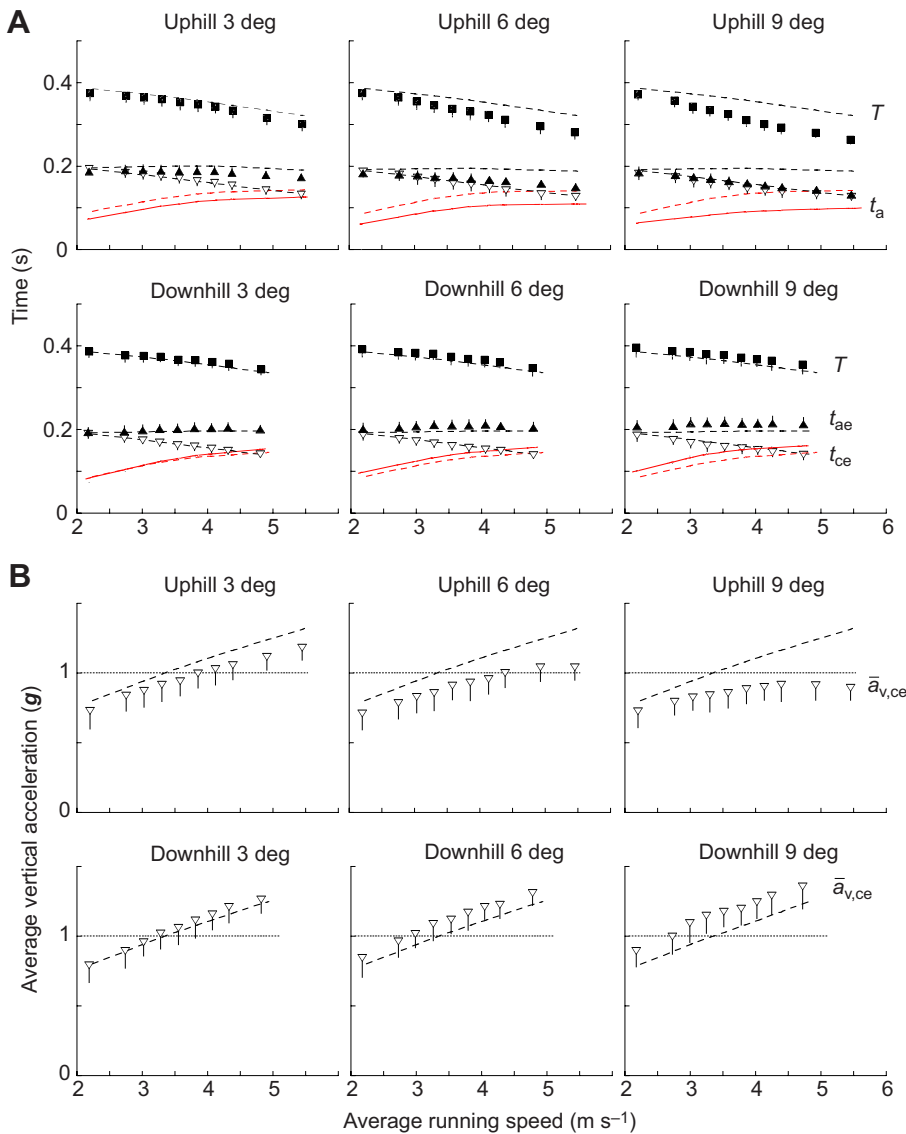
was computed by:

$$a_v(i) = \frac{F_v(i) - BW}{m} = \frac{b}{m} - \frac{k}{m}S(i) + \frac{c}{m}V_v(i), \quad (9)$$

where  $a_v(i)$ ,  $V_v(i)$  and  $S(i)$  were the experimental data at instant  $i$ . In this way,  $n$  equations were produced, where  $n$  is the number of samples during contact. This set of equations resulted in an over-constrained system, from which the constant ( $b/m$ ), the mass-specific stiffness ( $k/m$ ) and the actuator coefficient ( $c/m$ ) were computed by a regression analysis using singular value decomposition that minimizes the sum of squared errors.

For running on the level, we also compared the values obtained from Eqns 7 and 8. In Eqn 8,  $c/m$  is close to zero and  $k/m$  differs by  $1.8 \pm 2.1\%$  (mean  $\pm$  s.d.,  $n=2440$ ) from Eqn 7.

The goodness of the spring-actuator-mass model was assessed by computing (1) the variance explained by the regression model ( $r^2$ ), and (2) the root mean square error (RMSE), which expresses the agreement between the measured and the computed values of the GRF.



**Fig. 4. Step duration and average vertical acceleration of the COM as a function of speed at each slope.** (A) At each slope, the filled squares indicate the step period ( $T$ ), the open triangles the effective contact time ( $t_{ce}$ ) and the closed triangles the effective aerial time ( $t_{ae}$ ). The red lines represent the aerial time ( $t_a$ ). The dashed lines are the results obtained on the level for  $T$ ,  $t_{ce}$ ,  $t_{ae}$  and  $t_a$  (weighted mean, Kaleidagraph 4.5). (B) At each slope, the open triangles indicate the average vertical acceleration of the COM during the effective contact time ( $\bar{a}_{v,ce}$ ). Dashed lines are the results obtained on the level and the horizontal dotted line represents 1 g. Other indications as in Fig. 3.

## Statistics

Data were grouped into speed–slope classes. To obtain one value per subject in each class, the steps of the same subject in a same class were averaged. The mean and standard deviation of the runner population were then computed in each class (grand mean). A two-way ANOVA with *post hoc* Bonferroni correction (PASW Statistics 19, SPSS, IBM, Armonk, NY, USA) was performed to assess the individual and interaction effects of speed and slope on the calculated variables ( $P$ -values were set at 0.05).

## RESULTS

### Effect of slope on the ratio between positive and negative work done

The mass-specific external work done per unit distance is plotted in Fig. 3A. In the fore-aft direction, the work done to move the COM horizontally ( $W_f$ ) increases similarly with speed at any slope ( $P=0.995$ ). Moreover, because subjects move at a constant speed,  $W_f^+ = W_f^-$ .

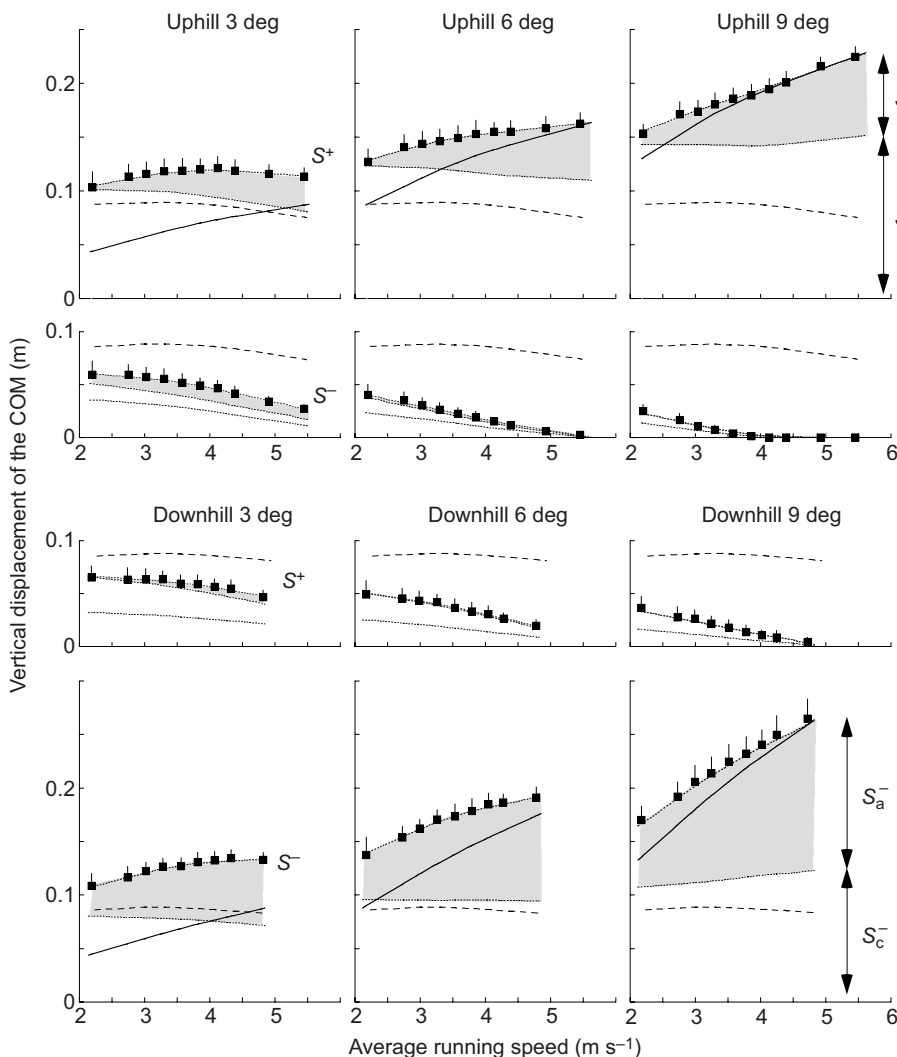
Therefore, the imbalance between  $W_{\text{ext}}^+$  and  $W_{\text{ext}}^-$  on a slope is only due to a modification in  $W_v^+$  and  $W_v^-$ . During uphill running,  $W_v^+$  increases, while  $W_v^-$  decreases and tends to disappear above  $\sim 4.4 \text{ m s}^{-1}$  at +6 deg and above  $\sim 3.3 \text{ m s}^{-1}$  at +9 deg. On a negative slope,  $W_v^+$  tends to disappear above  $\sim 5.0 \text{ m s}^{-1}$  at –6 deg and above  $\sim 4.2 \text{ m s}^{-1}$  at –9 deg.

Note that the ratio  $W_{\text{ext}}^-/W_{\text{ext}}^+$  changes with slope ( $P<0.001$ ), but is independent of speed ( $P=0.17$ ):  $W_{\text{ext}}^-/W_{\text{ext}}^+$  equals 0.5 at 0 deg, but decreases monotonically below 0.5 on a negative slope and increases monotonically above 0.5 on a positive slope (Fig. 3B).

### Effect of slope and speed on step period

The step period ( $T$ ) is given as a function of running speed in Fig. 4A. The slope has a significant effect on the step period ( $P<0.001$ ):  $T$  decreases when running uphill, whereas it increases when running downhill. The effect of slope on  $T$  is more marked on positive than on negative slopes, though this effect is significant at all slopes (Bonferroni *post hoc*,  $P<0.01$ ). The slope does not affect the effective contact time  $t_{\text{ce}}$ , except at +9 deg (Bonferroni *post hoc*,  $P<0.01$ ). Thus, the change in  $T$  is mainly due to a change in  $t_{\text{ac}}$  ( $P<0.001$ ), which in turn, is largely due to a change in  $t_a$ .

When running on the level, the step is symmetric (i.e.  $t_{\text{ac}} \approx t_{\text{ce}}$ ) at speeds up to  $\sim 2.8 \text{ m s}^{-1}$  (Bonferroni *post hoc*,  $P<0.01$ ). These results are consistent with those reported in the literature (Cavagna et al., 1988; Schepens et al., 1998). When running uphill,  $t_{\text{ac}} \approx t_{\text{ce}}$  in a larger range of speeds because the mean vertical acceleration during  $t_{\text{ce}}$  ( $\bar{a}_{v,\text{ce}}$ ) is kept smaller than  $1 \text{ g}$  at higher speeds than on the level (Fig. 4B): up to  $\sim 3.3 \text{ m s}^{-1}$  at +3 deg, to  $\sim 3.9 \text{ m s}^{-1}$  at +6 deg and to  $5.6 \text{ m s}^{-1}$  at +9 deg. When running downhill, the difference



**Fig. 5. Vertical displacement of the COM as a function of speed at each slope.** At each slope, the filled squares indicate the upward ( $S^+$ , upper panel) and downward ( $S^-$ , bottom panel) vertical displacement of the COM. The grey zone ( $S_a$ ) represents the fraction of the vertical displacement taking place during the aerial phase, whereas  $S_c$  is the vertical displacement taking place during the contact phase. The dashed lines indicate  $S$  during level running. The continuous line represents  $S_{\text{min}}$ , the minimum vertical displacement to overcome the slope during the step. Note that  $S_{\text{min}}$  increases with speed because the step length increases. Other indications as in Fig. 3.

between  $t_{ae}$  and  $t_{ce}$  tends to increase because  $\bar{a}_{v,ce}$  becomes  $>1 g$  at speeds lower than those on the level. Consequently, the range of speeds at which  $t_{ae} \approx t_{ce}$  becomes narrower, i.e. below  $\sim 2.2 \text{ m s}^{-1}$  at  $-6$  and  $-9$  deg.

### Effect of slope and speed on the upward and downward displacements of the COM

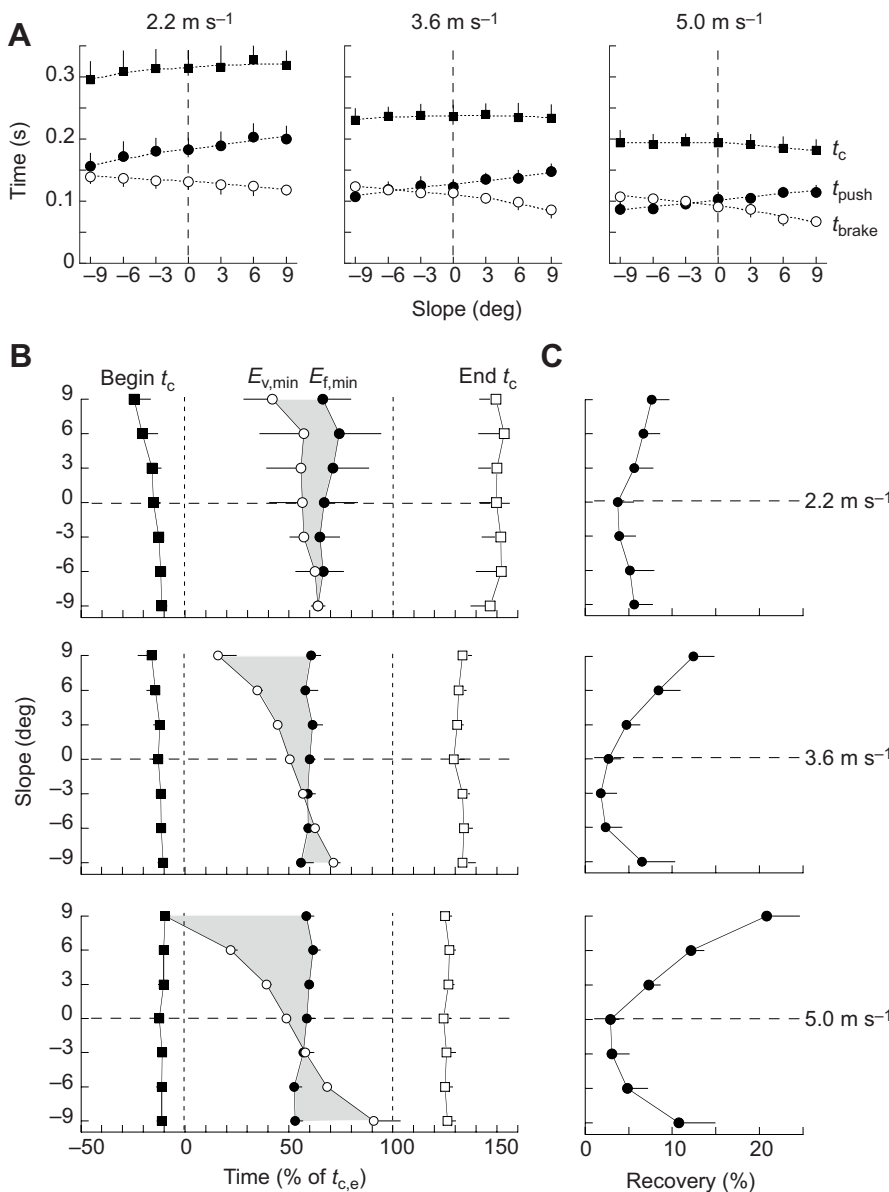
On the level, the upward ( $S^+$ ) and downward ( $S^-$ ) displacements of the COM over one step are equal (Fig. 5). On a slope, the difference between  $S^+$  and  $S^-$  increases with inclination ( $P < 0.001$ ).

When running uphill,  $S^+$  increases with slope and speed. At slow speeds, the displacement upwards during the aerial phase ( $S_a^+$ ) is almost nil, whatever the slope. When speed increases,  $S_a^+$  represents a greater part of  $S^+$ . The displacement downwards ( $S^-$ ) decreases when slope and speed increase:  $S^-$  disappears above  $5.0 \text{ m s}^{-1}$  at  $+6$  deg and above  $3.9 \text{ m s}^{-1}$  at  $+9$  deg. Note that the reduction of  $S^-$  is first due to a reduction of  $S_a^-$ . At  $+6$  deg and  $+9$  deg,  $S_a^-$  is almost nil at all speeds, suggesting that  $V_v$  at touchdown is close to zero.

When running downhill, the opposite phenomenon is observed:  $S^-$  increases and  $S^+$  decreases with slope and speed. The effect of slope and speed is more marked on  $S^-$  when running downhill than on  $S^+$  when running uphill. When running downhill,  $S_a^-$  represents a significant part of  $S^-$ , whereas  $S_a^+$  is almost nil whatever the slope and speed, indicating that  $V_v$  at take-off is close to zero.

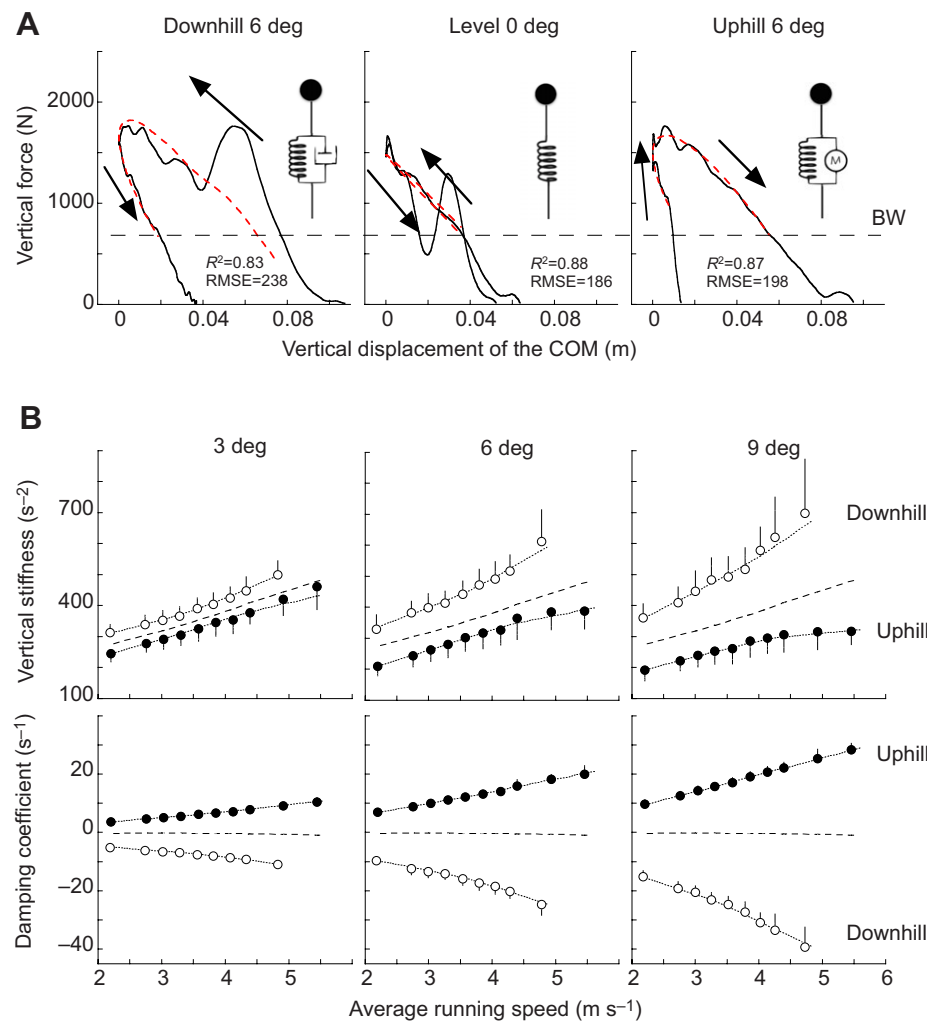
### Effect of slope and speed on the energy fluctuations of the COM

When running on a slope, muscles are compelled to modify the ratio between concentric and eccentric contraction. Consequently, the timing of negative and positive work production during  $t_c$  is modified (Fig. 6A). The time during which muscles perform negative external work ( $t_{brake}$ ) is extended during downhill running ( $P < 0.001$ ) while the duration of the positive work phase ( $t_{push}$ ) is increased during uphill running ( $P < 0.001$ ). Because at a given speed,  $t_c$  does not change significantly with slope (Fig. 6A), the modification of  $t_{brake}$  is compensated by an opposite change in  $t_{push}$ .



**Fig. 6. Contact time and energy transduction between  $E_f$  and  $E_v$  during the contact phase as a function of slope at low, intermediate and fast speeds.** (A) In each panel, the contact time ( $t_c$ , filled squares) is plotted as a function of slope and is divided into the time during which muscles perform positive external work ( $t_{push}$ , filled circles) and the time during which muscles perform negative external work ( $t_{brake}$ , open circles). The vertical dashed lines correspond to running on the level. The dotted lines are drawn through the data (weighted mean, Kaleidagraph 4.5). (B) The abscissa represents the relative time expressed as a percentage of  $t_{ce}$  and the ordinate represents the different slopes studied. Filled and open squares correspond, respectively, to the touchdown and take-off. The vertical dashed lines represent the beginning and end of  $t_{ce}$ . Note that the period between touchdown and the beginning of  $t_{ce}$  and the period between the end of  $t_{ce}$  and take-off change little with slope. Both the  $E_f$  and the  $E_v$  curves decrease during the first part of contact, and increase during the second part (Fig. 2). The open and filled symbols represent, respectively, the time at which the  $E_v$  and  $E_f$  curves reach a minimum ( $E_{v,min}$  and  $E_{f,min}$ ). The grey zone illustrates the period during which an energy transduction between  $E_v$  and  $E_f$  is possible because one curve is still decreasing while the other has begun to increase. Note that the instant of  $E_{f,min}$  changes little with slope. As compared with level running,  $E_{v,min}$  appears earlier in the stride on positive slopes and later on negative slopes. (C) The amount of energy recovered during the phase encompassed between the two minima of  $E_f$  and  $E_v$ , computed by Eqn 6, is presented at each slope for the three speeds. The horizontal dashed lines correspond to running on the level. Other indications as in Fig. 3.





**Fig. 7. Mechanical model of running on a slope.** (A) Typical trace of the vertical force  $F_v$  during the contact period ( $t_{ce}$ ) plotted as a function of vertical displacement  $S$  during running at  $\sim 3.6 m s^{-1}$ . The left panel corresponds to running at  $-6$  deg, the middle panel to  $0$  deg and the right panel to  $+6$  deg. The upwards arrow indicates the downward movement of the COM taking place during the first part of  $t_{ce}$ ; the downwards arrow indicates the upward movement of the COM taking place during the second part of  $t_{ce}$ . The black dashed line corresponds to  $F_v=BW$ . The red dashed line corresponds to the predicted value of  $F_v$  computed using Eqn 9 during  $t_{ce}$  using the values of  $b$ ,  $k$  and  $c$  obtained by the regression analysis. Tracings are from a male subject (height: 1.83 m, body mass: 70.0 kg, age: 31 years). The  $r^2$  and RMSE values are indicated on each trace. The insets illustrate the model used in downhill (a spring in parallel with a damper), level (a single spring) and uphill (a spring in parallel with a motor) running. (B) The upper row presents the mass-specific vertical stiffness  $k/m$  as a function of speed, and the lower row the mass-specific coefficient  $c/m$  of the actuator. The left column corresponds to a slope of 3 deg (open circles for downhill running and filled circles for uphill running), the middle column to a slope of 6 deg and the left column to 9 deg. Dashed lines correspond to level running. The dotted lines are drawn through the data (weighted mean, Kaleidagraph 4.5). Other indications as in Fig. 3.

The relative time of occurrence of the minimum of  $E_f$  ( $E_{f,min}$ ) changes little with slope [see Figs 2 (arrows) and 6B]. On the contrary, the minimum of  $E_v$  ( $E_{v,min}$ ) appears relatively earlier during contact in uphill running and later in downhill running. The effect of the slope on the relative time of occurrence of  $E_{v,min}$  is more accentuated when speed increases. Between  $E_{f,min}$  and  $E_{v,min}$ , the  $E_f$  and  $E_v$  curves (grey zone in Fig. 6B) are out of phase and an energy exchange can occur from  $E_f$  to  $E_v$  when  $E_{v,min}$  precedes  $E_{f,min}$ , and from  $E_v$  to  $E_f$  when  $E_{f,min}$  precedes  $E_{v,min}$ . This exchange of energy allows recovery of a significant amount of energy (i.e. %R>10%) only on steep slopes and at speeds  $>3.6 m s^{-1}$  (Fig. 6C).

### Modelling running on a slope

When running on a slope, the lower-limb muscles can be modelled as a mass mounted on a spring in parallel with an actuator that generates a muscular driving force proportional to the vertical velocity of the COM and produces (uphill) or absorbs (downhill) energy during  $t_{ce}$ . The overall mass-specific stiffness  $k/m$  and the actuator coefficient  $c/m$  generated by the lower-limb muscles (Fig. 7B) are modified by both the slope of the terrain and the speed of progression ( $P<0.001$ ). Compared with at  $0$  deg,  $k/m$  decreases on a positive slope and increases on a negative slope. At a given slope,  $k/m$  increases with velocity, though the effect of speed is greater on negative than positive slopes ( $P<0.001$ ).

During level running, the complex musculoskeletal system of the lower limb behaves like a single linear spring and  $c/m$  is nil. Running uphill requires additional energy to overcome the slope. In this case,  $c/m$  is positive and increases with the mechanical demands, i.e. with increasing slope but also with increasing speed. On the contrary, running downhill requires dissipation of energy. Consequently,  $c/m$  is negative and its absolute value increases when slope becomes steeper and when speed increases. Note also that the effect of speed on  $c/m$  is greater on negative than on positive slopes ( $P<0.001$ ).

This model describes the basic vertical oscillation of the COM during running on a slope (Fig. 7A) without taking into account the first peak in the  $F_v$  curve as a result of foot slap (Alexander et al., 1986; Schepens et al., 2000) and the vibrations of the treadmill motor (Fig. 1); the  $r^2$  of the least square method is always  $>0.63$  and RMSE ranges between 120 and 440 N (Table 1).

### DISCUSSION

This study was intended to help understand how the bouncing mechanism is modified when the slope of the terrain becomes positive or negative. Our results show that the bouncing mechanism still exists on shallow slopes and progressively disappears when the slope increases. This mechanism disappears earlier on positive than on negative slopes and earlier at high speeds than at slow speeds. In this section, we will discuss how

**Table 1. Coefficient of determination and root mean square error (RMSE) of the model**

Slope (deg)	Speed (m s <sup>-1</sup> )									
	2.2	2.8	3.1	3.3	3.6	3.9	4.2	4.4	5.0	5.6
9	0.80±0.04 217±45	0.80±0.04 232±52	0.78±0.04 246±51	0.77±0.05 250±55	0.76±0.05 254±54	0.75±0.05 259±49	0.74±0.07 269±53	0.72±0.05 280±46	0.70±0.04 280±52	0.66±0.06 307±37
6	0.86±0.03 182±35	0.87±0.03 188±42	0.87±0.03 194±43	0.86±0.03 206±43	0.85±0.02 210±43	0.84±0.03 226±48	0.83±0.04 234±48	0.82±0.04 242±51	0.77±0.03 276±50	0.75±0.05 295±54
3	0.93±0.01 139±29	0.92±0.01 146±31	0.92±0.02 155±33	0.91±0.02 167±35	0.90±0.02 178±28	0.89±0.02 189±33	0.87±0.02 209±29	0.86±0.03 216±33	0.82±0.06 258±43	0.75±0.1 312±52
0	0.94±0.02 120±29	0.92±0.03 153±37	0.90±0.05 175±48	0.87±0.04 200±37	0.86±0.06 210±39	0.84±0.05 238±49	0.80±0.07 264±51	0.78±0.07 291±55	0.72±0.1 347±71	0.68±0.1 400±89
−3	0.93±0.05 125±40	0.93±0.02 142±28	0.92±0.02 153±33	0.91±0.02 170±33	0.90±0.03 188±44	0.88±0.04 203±34	0.86±0.04 230±49	0.84±0.04 251±48	0.77±0.07 308±66	
−6	0.81±0.2 207±98	0.86±0.07 207±60	0.86±0.04 211±43	0.84±0.04 234±51	0.83±0.04 248±55	0.82±0.05 269±66	0.8±0.04 289±60	0.77±0.04 311±60	0.72±0.06 369±64	
−9	0.77±0.1 248±63	0.75±0.1 292±62	0.76±0.09 297±64	0.73±0.08 330±84	0.71±0.11 339±88	0.70±0.08 357±75	0.70±0.06 372±73	0.68±0.06 392±82	0.63±0.1 444±91	

The mass-specific stiffness ( $k/m$ ) and damping/motor coefficient ( $c/m$ ) during  $t_{ce}$  were evaluated using a least-squares method. In each class, the first line corresponds to the  $r^2$  and the second to the RMSE (expressed in N).

Data are grand means (see Materials and methods)±s.d. In each class,  $n=10$  except for (+6 deg; 5.6 m s<sup>-1</sup>) and (+9°; 5.0 m s<sup>-1</sup>), where  $n=9$ , and for (+9 deg; 5.6 m s<sup>-1</sup>), where  $n=7$ .

the step period, the vertical movement of the COM and the energy fluctuation of the COM affect the bouncing mechanism of running. We will also show that these variables are tuned to contain the increase in the positive or negative muscular work and power that is due to slope. We finally discuss the quality and limits of the mechanical model describing the vertical movement of the COM during slope running.

### Change in step period with slope

Minetti et al. (1994) show that on a positive slope the step period  $T$  decreases significantly, whereas on a negative slope  $T$  tends to increase (though this increase is not significant). Our results confirm that, at a given speed,  $T$  is shorter when running uphill than when running on the level. On the contrary, during downhill running, our results show a significant increase in  $T$ , even if this change is less marked than on a positive slope. This discrepancy with the results of Minetti and colleagues may be explained by the fact that the number of steps analysed here ( $n=15,760$  steps) is higher than that in Minetti's study ( $n=418$  steps).

In our study, we observe that  $t_c$  (Fig. 6A) and  $t_{ce}$  (Fig. 4A) at a given speed do not change significantly with slope, in both downhill and uphill running (except at +9 deg at the highest speeds). The change in the step period  $T$  is thus mainly due to a change in  $t_a$ , which in turn changes  $t_{ae}$ .

As shown by Cavagna et al. (1991), running on flat terrain with a long effective aerial phase is a convenient strategy to decrease the average power developed over the step, provided that muscles are able to develop enough power during the push. Our results suggest that the changes in  $t_{ae}$  are intended to contain the additional muscular power due to the slope.

When running uphill as compared with running on the level,  $T$  decreases because  $t_{ae}$  is reduced. Because  $t_{ce}$  is not modified by slope, the step remains symmetric (i.e.  $t_{ce} \approx t_{ae}$ ) at higher speeds than on flat terrain. These results are similar to those obtained when running on the level in hyper-gravity (Cavagna et al., 2005): at 1.3 g, the rebound remains symmetric up to 4.4 m s<sup>-1</sup>.

At a given speed and for a given  $t_{ce}$ , a symmetric rebound results in a shorter step than does an asymmetric rebound. As a result, the minimal height ( $S_{min}$ ) that the COM must gain each step is smaller, the impact against the ground is reduced and the force and power

during the push are decreased (Cavagna et al., 1991). However, decreasing  $T$  results in a greater internal power to move the limb segments relative to the COM.

Snyder and Farley (2011) have observed that the optimal step period at which the oxygen consumption is minimal does not change for slopes between −3 and +3 deg. However, these authors show that the freely chosen  $T$  decreases slightly between 0 and 3 deg. This decrease in  $T$  might be a strategy to contain the mechanical power during the push.

The changes observed in uphill running are similar to those observed in old men running (Cavagna et al., 2008b). In older subjects, the average upward acceleration ( $\bar{a}_{v,ce}$ ) is lower than in younger ones, leading to a symmetric rebound. According to these authors, the lower force attained during contact by the old subjects may be explained in part by the loss of muscular strength (e.g. Doherty, 2003). Similarly, the strategy adopted while running uphill could be due to the limits set by the muscular strength and/or power. Furthermore, in uphill running, the GRF vector is farther from the leg joint centres (DeVita et al., 2007). Thus, the slope of the terrain alters the muscle mechanical advantage by creating longer lever arms, and leads to higher joint torques and power outputs (Roberts and Belliveau, 2005). Therefore, decreasing  $T$  might be a beneficial strategy to limit the muscular moments and to reduce the mechanical load applied to the MTU.

At the opposite, when running downhill,  $T$  increases as compared with running on the level because  $t_{ae}$  increases. Because  $t_{ce}$  is not modified, steps are asymmetric (i.e.  $t_{ce} < t_{ae}$ ) at lower speeds than on a flat terrain. These results are similar to those obtained when running in unweighted conditions (Sainton et al., 2015): when BW is reduced by 40%,  $t_c$  remains unchanged while  $t_a$  is increased.

The step asymmetry has the physiological advantage to limit the internal power. However, this asymmetry requires a greater  $\bar{a}_{v,ce}$  and, consequently, a greater power during  $t_{ce}$ . The choice of this strategy in downhill running may be due to the difference in force exerted during negative and positive work phases: during downhill running, muscles contract mainly eccentrically, allowing the development of higher forces. Moreover, in downhill running, runners land with the leg more extended (Leroux et al., 2002), resulting in reduction of the lever arms of the GRF about the lower-limb joints and thus of the net muscular moments.

### Change in vertical motion of the COM

When running uphill at a given speed, to maintain the bouncing mechanism similar to level running, the runners should increase  $W_{\text{ext}}^+$  to overcome the slope, without changing  $W_{\text{ext}}^-$  (Fig. 3A). However, the runner limits  $W_{\text{ext}}^+$  by reducing  $W_{\text{ext}}^-$ . The opposite phenomenon is observed during downhill running, where  $W_{\text{ext}}^-$  is limited by reducing  $W_{\text{ext}}^+$ . Because the work done to accelerate and decelerate the COM forwards ( $W_f$ ) does not change with slope, the change in  $W_{\text{ext}}^+$  and  $W_{\text{ext}}^-$  is due to a change in  $W_v^+$  and  $W_v^-$ , which in turn is mainly due to a modification of  $S^+$  and  $S^-$  during the step (Fig. 5).

When running uphill, the upward displacement of the COM each step ( $S^+$ ) increases with slope and speed because  $S_{\text{min}}$  increases. In contrast, the downward displacement ( $S^-$ ) decreases. At low speeds and on shallow slopes,  $S^-$  is still present because the muscular power at disposal during the push is great enough to increase  $S^+$  beyond  $S_{\text{min}}$ . In this way, the presence of  $S^-$  allows the storage of elastic energy into the MTU to be restored during the next positive work phase. On the contrary, at high speeds and on steep slopes, the power during the push approaches the maximal performance of the runner. Therefore,  $S^+$  is maintained close to  $S_{\text{min}}$ ; consequently,  $S^-$  and  $W_v^-$  (Fig. 3A) are almost nil and no rebound is possible.

When running downhill,  $S^-$  increases faster with slope and speed than  $S^+$  in uphill running (Fig. 5); these changes in  $S^-$  are mainly due to a change in the downward fall of the COM during  $t_a$  ( $S_a^-$ ). In contrast, the effect of slope and speed on  $S^+$  on a negative slope is less marked than the changes in  $S^-$  on a positive slope. Consequently, when running downhill, the possibility of elastic storage increases with speed and slope. Though, as mentioned by Snyder and Farley (2011) and Snyder et al. (2012), the recoil is limited because  $S^+$  and  $W_v^+$  are small.

Furthermore, the large  $S_a^-$  observed in downhill running results in a high  $V_v$  at touchdown, which in turn causes greater GRF. According to Zelik and Kuo (2012), the vibrations of the soft tissues induced by the impact could reduce the muscular work done by dissipating energy.

### Change in the energy fluctuations of the COM

Running is thought to employ a spring-mass mechanism by which interactions between the COM and the ground allow storage and release of elastic energy in the MTU. *In vivo* measurements of muscle–tendon interaction have highlighted the influence of the stretch–recoil of tendons on the power output of muscles during running (Ishikawa and Komi, 2008; Roberts et al., 2007).

On the level at low and intermediate speeds,  $t_{\text{push}} > t_{\text{brake}}$  (Fig. 6A), although  $W_{\text{ext}}^+ = W_{\text{ext}}^-$ . This difference in time is due to the greater muscular force exerted during the eccentric phase. The fact that  $t_{\text{push}} > t_{\text{brake}}$  thus suggests an important contribution of the contractile machinery to the MTU length change and to the work production (Cavagna, 2006). At higher speeds (i.e. above  $\sim 3.9 \text{ m s}^{-1}$ ),  $t_{\text{push}} = t_{\text{brake}}$ , which suggests that when muscle activation is progressively augmented with increasing speed, the MTU length change is mainly due to tendon length change. The work contribution by the contractile machinery is thus progressively substituted by elastic storage and recovery by tendons. The  $t_{\text{push}}/t_{\text{brake}}$  ratio may therefore be an expression of the deviation of the MTU's response from that of an elastic structure. On a slope, the change in the ratio between  $W_{\text{ext}}^+$  and  $W_{\text{ext}}^-$  most likely affects the interaction between muscle and tendons during the stretch–shortening cycle (Roberts and Azizi, 2011).

When running uphill, the linear increase of  $W_{\text{ext}}^+$  changes the partitioning of  $t_c$  into  $t_{\text{push}}$  and  $t_{\text{brake}}$  (Fig. 6A). In order to contain the average muscular power required during the push,  $t_{\text{push}}$  increases with slope and  $t_{\text{push}} > t_{\text{brake}}$ . This suggests that the MTU length

change is mainly due to a shortening of the contractile machinery and that less elastic energy is stored – as in old men running on the level (Cavagna et al., 2008a). As proposed by Roberts and Azizi (2011), it could be that on a positive slope, MTUs work like power amplifiers: the energy produced during the muscular contraction is stored at a low pace in the tendons to be released at a higher pace.

In downhill running when slope becomes steeper, in order to limit the power during the brake,  $t_{\text{brake}}$  increases and  $t_{\text{push}}$  becomes shorter. The higher GRF observed in downhill running could favour the role of the tendon relative to that of muscle: muscle would perform a quasi-isometric contraction and the energy would be stored in the tendon during rapid stretch, to be dissipated later by a slower lengthening of the muscle (Roberts and Azizi, 2011).

The partition between  $t_{\text{push}}$  and  $t_{\text{brake}}$  changes because the minimum of  $E_v$  appears increasingly earlier in uphill running and increasingly later in downhill running, whereas the minimum of  $E_f$  occurs always more or less in the middle of the contact period (Fig. 6B and arrows in Fig. 2). For this reason, when slope increases, a phase shift between  $E_f$  and  $E_v$  emerges and an energy transduction between these two forms of energy can occur.

When running uphill, the lower limb acts like a pole in athletics (Schade et al., 2006). During the first part of contact (i.e. period between the two arrows in the upper panels of Fig. 2), the COM loses horizontal velocity, while it gains height and vertical velocity. During this phase, there is an energy transduction between  $E_f$  and  $E_v$ . The fact that  $E_{\text{ext}}$  decreases shows that the loss in  $E_f$  is greater than the gain in  $E_v$ ; part of the  $E_{\text{ext}}$  lost is stored in the elastic element of the MTU to be released during the second part of contact to increase the kinetic and potential of the COM. Note that the same phenomenon during the running step preceding the jump over an obstacle was described by Mauroy et al. (2013).

When running downhill, the energy transduction occurs during the second part of the contact, when  $E_v$  is decreasing while  $E_f$  increases. In this case, the potential energy lost is used to accelerate the COM forward.

In level running, the energy recovered through an exchange between  $E_v$  and  $E_f$  (Eqn 6) is negligible ( $\%R < 5\%$ ), like in a spring-mass system (Cavagna et al., 1976). When running at high speed on steep slopes, the rebound of the body deviates from a spring-mass system. However, the energy transduction allows recovering only a small amount of energy: at best  $\%R \approx 20\%$  in uphill running and  $\%R \approx 10\%$  in downhill running.

### Model of the vertical bounce of the body

In this study, we propose a model that reproduces in first approximation the basic oscillation of a spring-mass actuator (see inset in Fig. 7A). The aim of this model is to understand how all of the lower-limb muscles are tuned to generate an overall leg stiffness and leg actuation to sustain the vertical oscillation of the bouncing system.

Running on a slope is not a pure elastic phenomenon because energy must be added or released at each step. Therefore, our model includes an actuator placed parallel to the spring. This actuator generates a force proportional to  $V_v$ ; a linear force–velocity relationship was chosen because functional tasks that involve all lower-limb joints show a quasi-linear relationship (Bobbert, 2012; Rahmani et al., 2001), rather than the classical hyperbolic relationship described in isolated muscles (Hill, 1938). The coefficient  $c/m$  is positive during uphill running, showing that the actuator adds energy to the system, and negative during downhill running, because energy is dissipated at each step. As speed and slope increase, the discrepancy between the upward and downward



displacement of the COM increases, the rebound of the COM deviates from a spring-mass system and the coefficient  $c/m$  increases.

On a slope,  $k/m$  decreases when running uphill and increases when running downhill. On a positive slope, in order to maintain the symmetry of the step,  $\bar{a}_{v,cc}$  remains  $\leq 1 g$  (Fig. 4B). This lower acceleration is most likely obtained by reducing the stiffness of the contractile elements of the MTU and the overall  $k/m$  becomes smaller than that on the level (Fig. 7B).

Note also that on positive slopes, the limbs at impact are more flexed to prevent pitching backward (Birni-Jeffery and Higham, 2014; Leroux et al., 2002). On the level, runners adopting a more crouched posture, similar to Groucho running (McMahon et al., 1987), present lower vertical GRF and consequently a smaller  $k/m$ . In uphill running, the more flexed posture during stance could explain, at least in part, the smaller  $k/m$ .

On a negative slope, the step is asymmetric at most speeds and slopes because  $\bar{a}_{v,cc} > 1 g$  (Fig. 4B). When acceleration increases, muscles fibres oppose a progressively greater force to stretching and the contractile machinery becomes stiffer than the tendon. Subsequently, the overall  $k/m$  becomes greater than on the level. Furthermore, increasing  $k/m$  minimizes the lowering of the COM during contact (Fig. 5). This strategy might serve as an intrinsic safety mechanism to limit the risk of MTU damage after landing (DeVita et al., 2008).

Our simple spring-actuator-mass model predicts the  $F_v$ -time curve, though it does not take into account the first peak in the  $F_v$  curve, which is due to foot slap (Alexander et al., 1986; Schepens et al., 2000). To estimate the contribution of the foot collision on the shape of the  $F_v$ -time curve, we used a Fourier series analysis (Clark and Weyand, 2014). This analysis decomposes the  $F_v$  signal into low- and high-frequency components. According to Clark and Weyand (2014), the high-frequency components are mainly due to the acceleration of the lower limb during the impact phase. In our study, we observed that the variance accounted for by these high-frequency components increases at high speeds and on steep negative slopes (see Table S1). This observation supports the idea that the decrease in goodness-of-fit indexes (Table 1) is due to a higher contribution of the foot's interaction with the ground.

These last results corroborate those of Clark and Weyand (2014) obtained in sprint running; they show that at swift speeds, the GRF waveform deviates from the simple spring-mass model pattern, most likely because of the greater importance of the foot-ground collision. Therefore, Clark and Weyand (2014) propose a model including two masses and springs to take into account the interaction of the lower-limb segments with the ground. Our spring-actuator-mass model could thus be refined by adding a second spring mass representing the foot and shank, although kinematic data of these segments are needed to feed this implemented model.

## Conclusions

Cavagna et al. (1991) suggested that running with a long aerial phase limits the step-average power as long as muscles are able to develop enough power during the push and/or the brake. Our results support this hypothesis.

When running uphill at a given speed, the average external power developed during the positive work phase seems to be the limiting factor. Actually, when slope increases, in order to keep a long aerial time  $t_a$ , the vertical velocity of the COM at take-off should increase because the minimal vertical displacement ( $S_{min}$ ) increases. This would require a greater power during the push. As a matter of fact, this power is limited by: (1) reducing  $t_a$  and thus the step period  $T$ ,

(2) increasing the duration of the push ( $t_{push}$ ) at the expense of the duration of the brake ( $t_{brake}$ ) and (3) reducing the downward displacement of the COM. As a result, uphill running deviates from a bouncing mechanism as speed and slope increases.

When running downhill, the average external power developed during the negative work phase seems to be the limiting factor. Indeed, despite a lower vertical velocity at take-off,  $t_a$  – and thus  $T$  – increases with slope and speed because the ballistic fall of the COM increases. A longer  $t_a$  increases the external power developed during the brake because the energy to be dissipated after touchdown is greater. In spite of better muscular performance during eccentric than concentric contraction, the power during the brake is limited by (1) increasing  $t_{brake}$  at the expense of  $t_{push}$  and (2) reducing the upward displacement of the COM. Consequently, the bouncing mechanism during downhill running gradually disappears as speed and slope increase.

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## Competing interests

The authors declare no competing or financial interests.

## Author contributions

Conceived and designed the experiments: A.D., P.L., P.W. Performed the experiments: A.D., P.L., P.W. Analyzed the data: A.D., P.L., P.W. Wrote the paper: A.D., P.L., P.W.

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## Supplementary information

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