

## RESEARCH ARTICLE

# An analysis of the rebound of the body in backward human running

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### SUMMARY

**Step frequency and energy expenditure are greater in backward running than in forward running. The differences in the motion of the centre of mass of the body associated with these findings are not known. These differences were measured here on nine trained subjects during backward and forward running steps on a force platform at 3–17 km h<sup>-1</sup>. In contrast to previous reports, we found that the maximal upward acceleration of the centre of mass and the aerial phase, averaged over the whole speed range, are greater in backward running than in forward running (15.7 versus 13.2 m s<sup>-2</sup>,  $P=1.9\times 10^{-6}$  and 0.098 versus 0.072 s,  $P=2.4\times 10^{-5}$ , respectively). Opposite to forward running, the impulse on the ground is directed more vertically during the push at the end of stance than during the brake at the beginning of stance. The higher step frequency in backward running is explained by a greater mass-specific vertical stiffness of the bouncing system (499 versus 352 s<sup>-2</sup>,  $P=2.3\times 10^{-11}$ ) resulting in a shorter duration of the lower part of the vertical oscillation of the centre of mass when the force is greater than body weight, with a similar duration of the upper part when the force is lower than body weight. As in a catapult, muscle–tendon units are stretched more slowly during the brake at the beginning of stance and shorten more rapidly during the push at the end of stance. We suggest that the catapult-like mechanism of backward running, although requiring greater energy expenditure and not providing a smoother ride, may allow a safer stretch–shorten cycle of muscle–tendon units.**

Key words: locomotion, running, backward running, step frequency, catapult.

### INTRODUCTION

Subjective evidence suggests that backward running provides a way to recover from injuries occurring in normal running while maintaining training. In order to substantiate this anecdotal evidence biomechanical aspects have been investigated aimed at measuring the differences between forward and backward running in the kinematics of body segments (Bates et al., 1986; Devita and Stribling, 1991), the ground reaction force and impulse (Threlkeld et al., 1989; Devita and Stribling, 1991), the energy expenditure (Flynn et al., 1994; Wright and Weyand, 2001), the lower limb joint moments of force and joint muscle powers (Devita and Stribling, 1991; Flynn and Soutas-Little, 1993) and the changes in foot–ground contact time (stance time) as a function of speed (Wright and Weyand, 2001). A common observation in all these studies is that the step frequency and the energy expenditure are greater in backward running than in forward running. The greater step frequency has been suggested to be due to a shorter stance time (Threlkeld et al., 1989) and a shorter flight time caused by a reduced vertical impulse with a similar swing/stance ratio (Threlkeld et al., 1989; Devita and Stribling, 1991). The peak vertical force during backward running was found to be lower than the peak vertical force in forward running (Threlkeld et al., 1989). The shorter stance time together with a greater muscle activation were considered to be the cause of the greater energy expenditure in backward running (Wright and Weyand, 2001). A recent study showed that the greater energy expenditure in backward running is due to a lower efficiency of positive work production (Cavagna et al., 2011), but the characteristics of the rebound resulting in this lower efficiency have

not been investigated. In particular the determinants of the step frequency in backward running are not clear.

Factors that determine the more economic choice of step frequency in forward running are: (i) tuning the step frequency to the natural frequency of the bouncing system, and (ii) choosing a step frequency that minimizes the total aerobic-limited step average power within the limits set by the anaerobic-limited push average power (Cavagna, 2010). The first strategy is usually adopted at low running speeds and abandoned for the second strategy at high running speeds by increasing the average upward acceleration above 1 *g* during the lower part of the vertical oscillation of the centre of mass. This results in a step frequency lower than the natural frequency of the system owing to a relatively greater duration of the upper part of the oscillation when the downward acceleration cannot exceed 1 *g*, but allows a lower step average power expenditure to reset the limbs at each step. In old age the first strategy is followed: the average upward acceleration never exceeds 1 *g*, the lower part of the oscillation equals that of the upper part and the step frequency is similar to the natural frequency of the system at all speeds. This allows development of a lower force during the push, but the increase in step frequency results in a greater power outlay to reset the limbs at each step (Cavagna et al., 2008a).

The apparent similarity between the characteristics of backward running hitherto reported in the literature and the mechanics of running in old age, i.e. a greater step frequency and energy expenditure, a lower vertical ground reaction force and a shorter flight time, suggests that the first of the two strategies mentioned above is adopted in backward running. However, the relationship between step frequency and natural frequency of the bouncing system in backward running is not known.

The rationale of the present study was to identify: (i) the changes in motion of the centre of mass of the body associated with the greater step frequency and energy expenditure found in backward running, and (ii) the effect of these changes in motion on the stretch–shorten cycle of muscle–tendon units during the rebound of the body. Is the greater step frequency due to a shorter duration of both the lower and the upper part of the oscillation of the centre of mass, as in old age? In other words, does backward running provide a smoother ride with a lower force exerted for each step on the ground as some studies suggest? How does the reversal of motion in backward running affect mechanical energy storage and release during the rebound of the body? To answer these questions, we studied subjects (experienced in backward running) during forward and backward running on soil at different speeds, and measured: (i) the amplitude and the duration of the vertical displacement of the centre of mass during stance, during the aerial phase and during the lower and upper part of the oscillation, (ii) the maximal upwards acceleration attained during the step, (iii) the within-step transduction between kinetic energy and gravitational potential energy of the centre of mass during the lift and the fall, (iv) the orientation in the sagittal plane of the impulse given by the ground reaction force during the push and the brake, and (v) the stiffness of the bouncing system.

## MATERIALS AND METHODS

The results described in this study were obtained on the same runs used previously (Cavagna et al., 2011) to determine negative–positive work durations and the external mechanical work done to maintain the motion of the centre of mass. As described below, the analysis was expanded in this study to obtain further novel information on the differences in the rebound of the centre of mass in forward and backward running (Figs 1–6). For the reader's convenience, the first part of the Materials and methods section briefly describes the experimental procedure used previously (Cavagna et al., 2011). The second part describes the additional measurement procedures made in the present study.

### Subjects

Experiments were carried out on subjects with on average 6 years of weekly backward running training (seven males and two females). The characteristics of the male subjects were: age  $43.3 \pm 6.2$  years, height  $1.72 \pm 0.06$  m and mass  $69.3 \pm 4.4$  kg (means  $\pm$  s.d.,  $N=7$ ). The characteristics of the female subjects were: age  $45.0 \pm 5.7$  years, height  $1.60 \pm 0.00$  m and mass  $54.1 \pm 7.6$  kg (means  $\pm$  s.d.,  $N=2$ ). Informed, written consent was obtained from each subject. The experiments were performed according to the Declaration of Helsinki.

### Instrumentation

The subjects ran forwards and backwards on a 50 m long indoor track that had built into it, at floor level 30 m from one end of the track, a strain gauge force platform sensitive to the forward and vertical component of the force exerted by the feet on the ground. The force platform dimensions (4 m long and 0.5 m wide) were large enough to avoid subjects altering their step length in the attempt to hit it. Two photocells placed  $\sim 3$  m apart alongside the platform were used to measure the average running speed. Mechanical details of the force platform and the procedures involved in using platform records have been thoroughly described in a previous study (Cavagna, 1975).

### Experimental protocol

The runners were asked to achieve and maintain a constant average speed over the platform. Subsequent runs started from opposite sides

of the track. The speed range was  $3\text{--}17\text{ km h}^{-1}$  ( $0.83\text{--}4.72\text{ m s}^{-1}$ ). Subjects were asked to voluntarily decrease their running speed to low values, below the metabolic walk–run transition, which has been estimated to be about  $6.5\text{ km h}^{-1}$  in backward running (Terblanche et al., 2003) and about  $7.4\text{--}8.1\text{ km h}^{-1}$  in forward running (Margaria, 1976; Terblanche et al., 2003). Nevertheless, the mechanics of running, and not that of walking, was maintained even at the lowest speeds. In fact, contrary to walking, the gravitational potential energy and the kinetic energy of forward motion of the centre of mass oscillated in phase during the steps analysed in this study, with a negligible transduction between them calculated as percentage recovery (Cavagna et al., 1976):  $0.9 \pm 1.1\%$  (mean  $\pm$  s.d.,  $N=107$ ) in backward running and  $1.9 \pm 1.8\%$  (mean  $\pm$  s.d.,  $N=104$ ) in forward running. Expanding the range of running speeds to low values expands the information on the relative amount of energy absorbed and restored by muscle *versus* tendon within muscle–tendon units at different durations of their stretch–shorten cycle (Cavagna, 2009).

### Data acquisition

The photocell signals and the platform signals, proportional to the ground reaction forces, were acquired at a rate of 500 Hz through a dedicated DAQ board (PCI MIO 16E, National Instruments, Austin, TX, USA) on a microcomputer. Custom LabVIEW (version 7.1, National Instruments) software programs were developed for data acquisition and subsequent analysis.

### Kinetic energy and gravitational potential energy of the centre of mass

Previous studies (e.g. Cavagna et al., 2008b) describe in detail the procedure followed to determine from the platform signals the instantaneous forward velocity  $V_f(t)$ , the instantaneous vertical velocity  $V_v(t)$ , the kinetic energy of forward motion  $E_{kf}(t) = 0.5M_b V_f(t)^2$  (where  $M_b$  is the mass of the body), the kinetic energy of vertical motion  $E_{kv}(t) = 0.5M_b V_v(t)^2$ , the vertical displacement of the centre of mass  $S_v(t)$ , the gravitational potential energy  $E_p(t) = M_b g S_v(t)$  (where  $g$  is the acceleration due to gravity), the translational kinetic energy in the sagittal plane  $E_k(t) = E_{kf}(t) + E_{kv}(t)$  and the total mechanical energy  $E_{cm}(t) = E_k(t) + E_p(t)$ . More details on this are provided in our previous paper (Cavagna et al., 2011).

### Lower and upper part of the rebound

The step period  $\tau$  and the vertical oscillation of the centre of mass  $S_v$  were divided into two parts: a lower part taking place when the vertical force measured by the force platform is greater than the body weight ( $t_{ce}$  and  $S_{ce}$ ), and an upper part taking place when the vertical force is smaller than body weight ( $t_{ae}$  and  $S_{ae}$ ). The step period and the vertical displacement were also divided, according to tradition, into the fractions taking place during the ground contact time ( $t_c$  and  $S_c$ ) and during the aerial time ( $t_a$  and  $S_a$ ). The measurement procedure and physical meaning of the  $S_v$  fractions are described in previous studies (e.g. Cavagna et al., 2008a).

### Transduction between kinetic energy and gravitational potential energy

The time course of the transduction,  $r(t)$ , taking place within the step between gravitational potential energy,  $E_p(t)$ , and translational kinetic energy in the sagittal plane,  $E_k(t)$ , was determined from the absolute value of the changes, both positive and negative, of  $E_p(t)$ ,  $E_k(t)$  and  $E_{cm}(t)$  in short time intervals within the step cycle:

$$r(t) = 1 - |\Delta E_{cm}(t)| / (|\Delta E_p(t)| + |\Delta E_k(t)|) \quad (1)$$

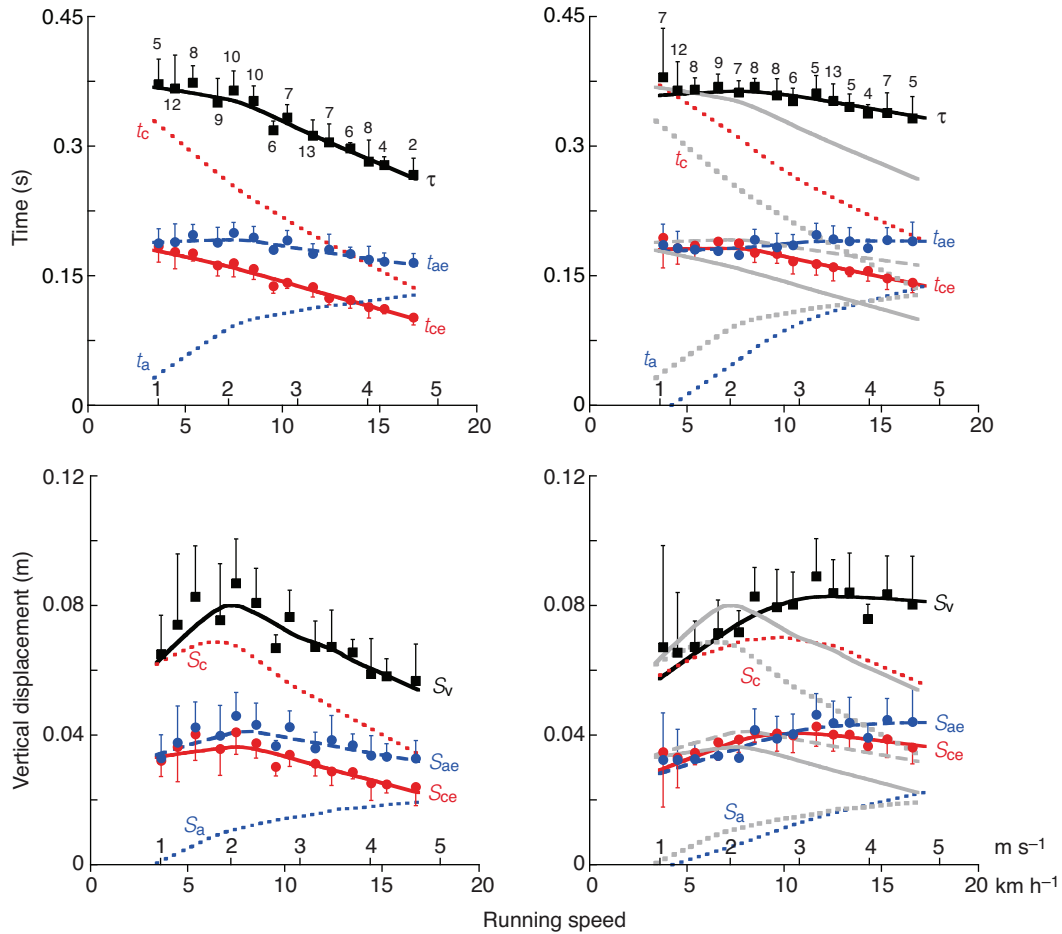


Fig. 1. Left panels: backward running. Right panels: forward running, with the backward running lines (grey) superimposed for comparison. The upper panels indicate the step period ( $\tau$ , filled black squares) and its fractions. The lower panels indicate the total vertical displacement during the step ( $S_v$ , filled black squares) and its fractions. The red circles indicate the time interval during which the vertical force is greater than body weight ( $t_{ce}$ ), and the vertical displacement during this time interval ( $S_{ce}$ ). The blue circles indicate the time interval during which the vertical force is lower than body weight ( $t_{ae}$ ), and the vertical displacement during this time interval ( $S_{ae}$ ). The red dotted line indicates the contact time ( $t_c$ ), and the vertical displacement ( $S_c$ ) during it. The blue dotted line indicates the corresponding aerial time ( $t_a$ ) and the vertical displacement ( $S_a$ ). The vertical bars indicate the standard deviation of the mean; the figures near the symbols in the upper panels indicate the number ( $N$ ) in the mean. Lines (Kaleidagraph 4.03, Synergy software, Reading, PA, USA, weighted fits) are just a guide for the eye and do not describe the underlying physical mechanism. Note that  $\tau$  and  $t_{ce}$  decrease with speed faster in backward running than in forward running, whereas  $t_{ae}$  is about equal in the two conditions and changes slightly with speed. This indicates that the fraction of the step cycle during which the vertical force is greater than body weight is relatively shorter in backward running than in forward running.

Note that when  $E_p(t)$  and  $E_k(t)$  increase and decrease in phase during the step no transduction can occur between them, the sum of their changes equals the change of  $E_{cm}(t)$ , and  $r(t)=0$ . When, in contrast, the changes of  $E_p(t)$  and  $E_k(t)$  are equal and have opposite sign the transduction between them is complete,  $\Delta E_{cm}(t)=0$  and  $r(t)=1$ . The cumulative value of energy recovery,  $R_{int}(t)$ , resulting from the instantaneous  $E_p-E_k$  transduction during the step, was measured from the area below the  $r(t)$  record divided by the step period:  $R_{int}(t)=(\int_0^t r(u)du)/\tau$ . At the end of the step  $R_{int}(\tau)=R_{int}$  (Cavagna et al., 2008b).

#### Vertical stiffness

The mass-specific vertical stiffness,  $k/M_b$ , is given by the slope of the relationship between vertical acceleration and vertical displacement of the centre of mass in the range corresponding to the amplitude of the oscillation of the spring-mass system, i.e. from its equilibrium position ( $F_v=M_b g$  and vertical acceleration  $a_v=0$ ) to its maximal deformation,  $S_{ce}$ , attained at the lowest point of the trajectory of the centre of mass of the body when  $a_v$  is at a maximum. In this study

we chose to measure the mass-specific vertical stiffness as  $k/M_b=a_{v,max}/S_{ce}$  (Cavagna et al., 2008a). The maximal upward acceleration  $a_{v,max}$  was measured by interpolation between the oscillations of the time derivative of  $V_v(t)$  using a quadratic least-squares fit (LabVIEW waveform peak detection VI). For comparison,  $k/M_b$  was also measured from the slope of a least-squares linear fit of the  $a_v$  versus  $S_v$  relationship from the equilibrium position to  $S_{ce}$ : (i) including data points obtained during both downward and upward displacement of the centre of mass ( $k/M_b$  up and down fit), and (ii) including data points obtained during the upward displacement only to avoid the oscillation in the  $a_v$  versus  $S_v$  record following the impact with the ground ( $k/M_b$  up fit). Furthermore the mass-specific vertical stiffness was measured as  $k/M_b$  half-period $=\pi/(2t_{ce})^2$  on the assumption that  $t_{ce}$  represents the half-period of the resonant frequency of the oscillating system  $f_s$ , i.e. that  $f_s=(k/M_b)^{0.5}/(2\pi)=1/(2t_{ce})$ .

Average values measured over the whole speed range were:  $k/M_b=a_{v,max}/S_{ce}=499.384\pm 192.621$  ( $s^{-2}$ ),  $k/M_b$  up and down fit $=454.051\pm 148.174$  ( $s^{-2}$ ),  $k/M_b$  up fit $=482.144\pm 171.079$  ( $s^{-2}$ ),  $k/M_b$  half-period $=491.778\pm 185.593$  ( $s^{-2}$ ) in backward running

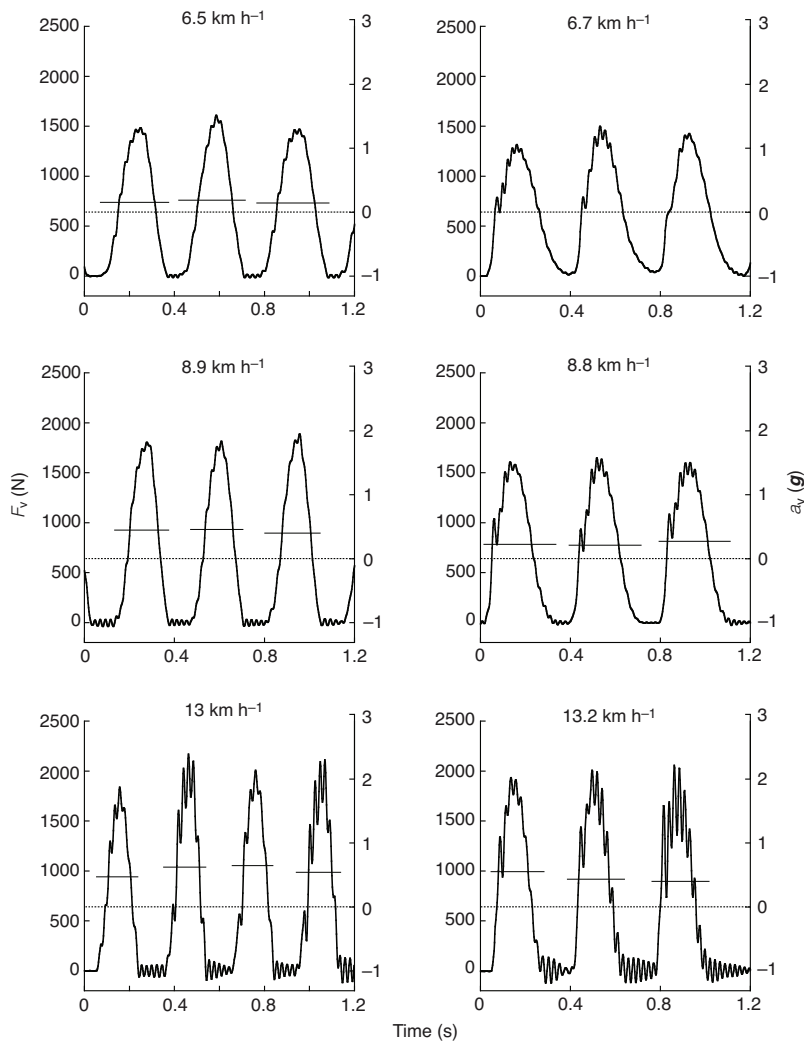


Fig. 2. Vertical force exerted on the ground by one subject (male, 40 years old, 65.2 kg mass, 1.72 m height, 10 years of backward running training) during steps of backward running (left) and forward running (right) at three different speeds. Same subject and runs as in fig. 1 of a previous study (Cavagna et al., 2011). The vertical acceleration of the centre of mass expressed as a multiple of the acceleration due to gravity is given on the right-hand ordinate. The dotted line indicates body weight. The continuous lines indicate the average force during stance (superimposed on the dotted line in the upper right panel where the aerial phase is nil). Note: (i) the sharp attainment of the aerial phase in backward running contrasting with the blunt attainment of the aerial phase in forward running, and (ii) the greater average force during stance in backward running.

(means  $\pm$  s.d.,  $N=107$ ); and  $k/M_b = a_{v,\text{mx}}/S_{\text{ce}} = 351.769 \pm 84.020$  ( $\text{s}^{-2}$ ),  $k/M_b$  up and down fit =  $308.496 \pm 67.493$  ( $\text{s}^{-2}$ ),  $k/M_b$  up fit =  $344.270 \pm 73.406$  ( $\text{s}^{-2}$ ),  $k/M_b$  half-period =  $347.821 \pm 84.992$  ( $\text{s}^{-2}$ ), in forward running (means  $\pm$  s.d.,  $N=104$ ).

The similarity of the mass-specific vertical stiffness measured as  $a_{v,\text{mx}}/S_{\text{ce}}$  and as  $(\pi/t_{\text{ce}})^2$  suggests that the duration of the lower part of the vertical oscillation of the centre of mass,  $t_{\text{ce}}$ , may indeed be considered to represent the half-period of the bouncing system.

We chose to use  $k/M_b = a_{v,\text{mx}}/S_{\text{ce}}$  as a measure less affected by: (i) the noise of the  $a_v$  versus  $S_v$  record following the impact with the ground, (ii) the assumption that the stiffness measured during the upward displacement only equals that during the upward and downward displacement, and (iii) the assumption that  $t_{\text{ce}}$  represents the half-period of the oscillating system. However, the mean values given above show that the conclusions reached in this study would not change using either of the methods described.

### Statistics

The data collected as a function of the running speed were grouped into the following speed intervals: 3 to  $<4 \text{ km h}^{-1}$ , 4 to  $<5 \text{ km h}^{-1}$ ...16 to  $<17 \text{ km h}^{-1}$  for backward running, and 3 to  $<4 \text{ km h}^{-1}$ , 4 to  $<5 \text{ km h}^{-1}$ ...16 to  $<17.5 \text{ km h}^{-1}$  for forward running. The data points in Figs 1, 3 and 6 represent the mean  $\pm$  s.d. in each of the above speed intervals and the numbers near the symbols in Fig. 1 give the number of items ( $N$ ) in the mean. In addition,

means ( $\pm$ s.d.) of the data obtained over the whole speed range ( $N=107$  for backward running and  $N=104$  for forward running) are given. When comparing the means of different variables within a subject group, with the same  $N$  value at a given running speed, a paired samples  $t$ -test was used to determine whether the means were significantly different. When comparing the means of different variables between two subject groups having different  $N$  values, a two-sample  $t$ -test assuming unequal variance was used. The values of  $P$  refer to the two-tail comparison (Microsoft Excel for Mac version 11.6.2).

## RESULTS

### Vertical oscillation of the centre of mass

The step period ( $\tau$ , upper panel) and the vertical displacement of the centre of mass during each step ( $S_v$ , lower panel) are given as a function of the running speed in Fig. 1 (black squares) with their fractions corresponding to the lower part of the oscillation ( $t_{\text{ce}}$  and  $S_{\text{ce}}$ , red circles) and to the upper part of the oscillation ( $t_{\text{ae}}$  and  $S_{\text{ae}}$ , blue circles). The fractions taking place during the ground contact phase ( $t_{\text{c}}$  and  $S_{\text{c}}$ , red dotted lines) and during the aerial phase ( $t_{\text{a}}$  and  $S_{\text{a}}$ , blue dotted lines) are also given for comparison. Left panels refer to running backwards, right panels to running forwards. A comparison of the left and right panels in Fig. 1 reveals the following.

(1) In backward running, as in forward running, the step period  $\tau = t_{\text{ce}} + t_{\text{ae}}$  decreases with speed. The decrease in  $\tau$  is due in both

cases to a decrease in duration of the lower part of the oscillation  $t_{ce}$  with a small change in duration of the upper part  $t_{ae}$ . In backward running  $t_{ce}$  decreases more rapidly with speed than in forward running, resulting in a sharper decrease in  $\tau$  and, as a consequence, in a sharper increase in step frequency  $f=1/\tau$ .

(2) In backward running, as in forward running, the duration of the lower part of the vertical oscillation is about equal to that of the upper part at the lowest running speed indicating that the rebound is symmetric, i.e.  $t_{ce} \approx t_{ae}$ . Because of the sharper decrease of  $t_{ce}$  in backward running, the difference between  $t_{ce}$  and  $t_{ae}$ , i.e. the on-off ground asymmetry of the rebound  $t_{ae}/t_{ce}$  (Cavagna, 2009), increases with speed more rapidly in backward running than in forward running. It is interesting to note that in both cases a division of the step based on the ground contact and aerial times ( $t_c$  and  $t_a$ , dotted lines in Fig. 1) reveals the largest asymmetry just when  $t_{ce}$  and  $t_{ae}$  show that the rebound is symmetric.

(3) In backward running, as in forward running, the vertical displacement of the centre of mass of the body,  $S_v$ , increases with speed to a maximum of  $\sim 0.08\text{m}$  that is attained at  $\sim 2\text{ms}^{-1}$  in backward running and at  $\sim 3.5\text{ms}^{-1}$  in forward running. Subsequently,  $S_v$  decreases with speed more rapidly in backward running than in forward running. Similarly to  $t_{ae}$  and  $t_{ce}$ , the corresponding vertical displacements  $S_{ae}$  and  $S_{ce}$  diverge earlier with increasing speed in backward running than in forward running.

**Vertical force during stance**

Fig. 2 shows the vertical force exerted on the force platform  $F_v$  and the corresponding vertical acceleration of the centre of mass of the body for one subject during backward and forward running steps at three different speeds. Note that the oscillation following heel strike during the increment of  $F_v$  in forward running is absent or markedly attenuated in backward running (Threlkeld et al., 1989), and that  $F_v$  falls sharply to zero in backward running whereas the aerial phase is attained through a gradual decrease of  $F_v$  in forward running. These observations are consistent with the finding that the landing–takeoff asymmetry is reversed in backward running (Cavagna et al., 2011). Note also that the mean vertical force exerted during stance (horizontal continuous lines) is on average greater in backward running than in forward running.

Fig. 3 shows the maximal upward acceleration  $a_{v,mx}$  attained at each step in backward running and in forward running. The straight lines are linear fits of all the data: backward  $a_{v,mx,b}$  ( $\text{m s}^{-2}$ )= $8.199+2.904V_f$  ( $\text{m s}^{-1}$ ) ( $R=0.778$ ) and forward  $a_{v,mx,f}$  ( $\text{m s}^{-2}$ )= $6.271+2.664V_f$  ( $\text{m s}^{-1}$ ) ( $R=0.836$ ). Averaged over the whole speed range,  $a_{v,mx}$  is  $\sim 18\%$  greater when running backwards ( $a_{v,mx,b}=15.682\pm 3.742\text{ m s}^{-2}$  versus  $a_{v,mx,f}=13.248\pm 3.464\text{ m s}^{-2}$ ,  $P=1.874\times 10^{-6}$ ).

**Transduction between potential and kinetic energy of the centre of mass**

In backward running the gravitational potential energy  $E_p$  and the kinetic energy of forward motion  $E_{kf}$  are even more precisely in phase than in forward running (see ‘Experimental protocol’ section in Materials and methods). It follows that the  $E_p-E_k$  transduction takes place essentially between  $E_p$  and  $E_{kv}$ . Fig. 4 shows that the  $E_p-E_k$  transduction attained at the end of the step  $R_{int}$  is greater in backward running than in forward running ( $R_{int,b}=0.421\pm 0.067$  versus  $R_{int,f}=0.360\pm 0.080$ ,  $P=1.385\times 10^{-8}$ ) due to a larger  $E_k$  into  $E_p$  transduction during the lift. In forward running the  $E_p-E_k$  transduction is greater during the descent than during the lift ( $0.208\pm 0.038$  versus  $0.152\pm 0.048$ ,  $P=7.244\times 10^{-34}$ ), whereas in backward running the  $E_p-E_k$  transduction is on average slightly

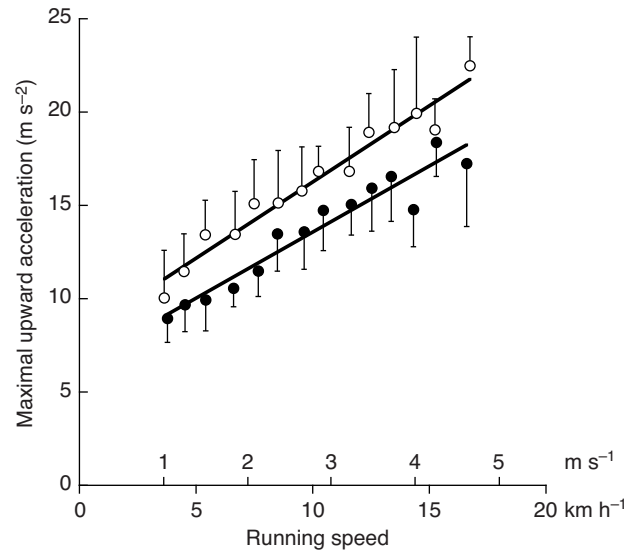


Fig. 3. The maximal positive (upward) acceleration attained by the centre of mass at the lowest point of its trajectory plotted as a function of speed in backward running (open circles) and in forward running (filled circles). Lines are linear fit of all the data. It can be seen that the maximal acceleration upwards is greater in backward running than in forward running. Statistical analysis as in Fig. 1.

greater during the lift than during the descent ( $0.216\pm 0.031$  versus  $0.205\pm 0.038$ ,  $P=1.916\times 10^{-7}$ ).

**Direction of the impulse given by the ground reaction force during the push and the brake**

The momentum of the centre of mass in the vertical direction,  $M_bV_v$ , is plotted as a function of the momentum of the centre of mass in the forward direction,  $M_bV_f$ , during the push (increment of  $M_bV_f$ ) and during the brake (decrement of  $M_bV_f$ ) in Fig. 5. Momentum in the vertical and forward directions is calculated from the corresponding kinetic energies  $E_{kv}$  and  $E_{kf}$ . Note that increments and decrements of momentum,  $M_b\Delta V$ , equal increments and decrements of the impulse,  $F\Delta t$ , where  $F$  is the ground reaction force. The red section of each plot indicates  $M_bV_v$  changes due to a vertical impulse with a vertical force exerted on the ground greater than body weight, resulting in an increase of  $M_bV_v$  from zero to its maximum (vertical lines) during the push and in a decrease of  $M_bV_v$  from its maximum to zero during the brake. The blue section of each plot indicates  $M_bV_v$  changes due to a vertical impulse with a vertical force less than body weight, resulting in a decrease of  $M_bV_v$  during the push and in an increase of  $M_bV_v$  during the brake. The light blue section indicates the aerial phase when  $M_bV_f$  is constant. The fraction of the push during which  $M_bV_v$  increases simultaneously with  $M_bV_f$  is given below each plot by the ratio  $a_{fv}/a_f$ . The fraction of the brake during which  $M_bV_v$  and  $M_bV_f$  simultaneously decrease is given by the ratio  $d_{fv}/d_f$ .

A comparison of the tracings obtained during the push in backward running (left column in Fig. 5) with those obtained during the brake in forward running (right column) shows that a vertical force greater than body weight is exerted over most of the push ( $\sim 85\%$ ) in backward running whereas it is exerted over most of the brake ( $\sim 90\%$ ) in forward running. In general, the data in Fig. 5 indicate that in backward running the impulse of the ground reaction force is directed more vertically during the push than during the brake, i.e.  $a_{fv}/a_f > d_{fv}/d_f$ , whereas in forward running

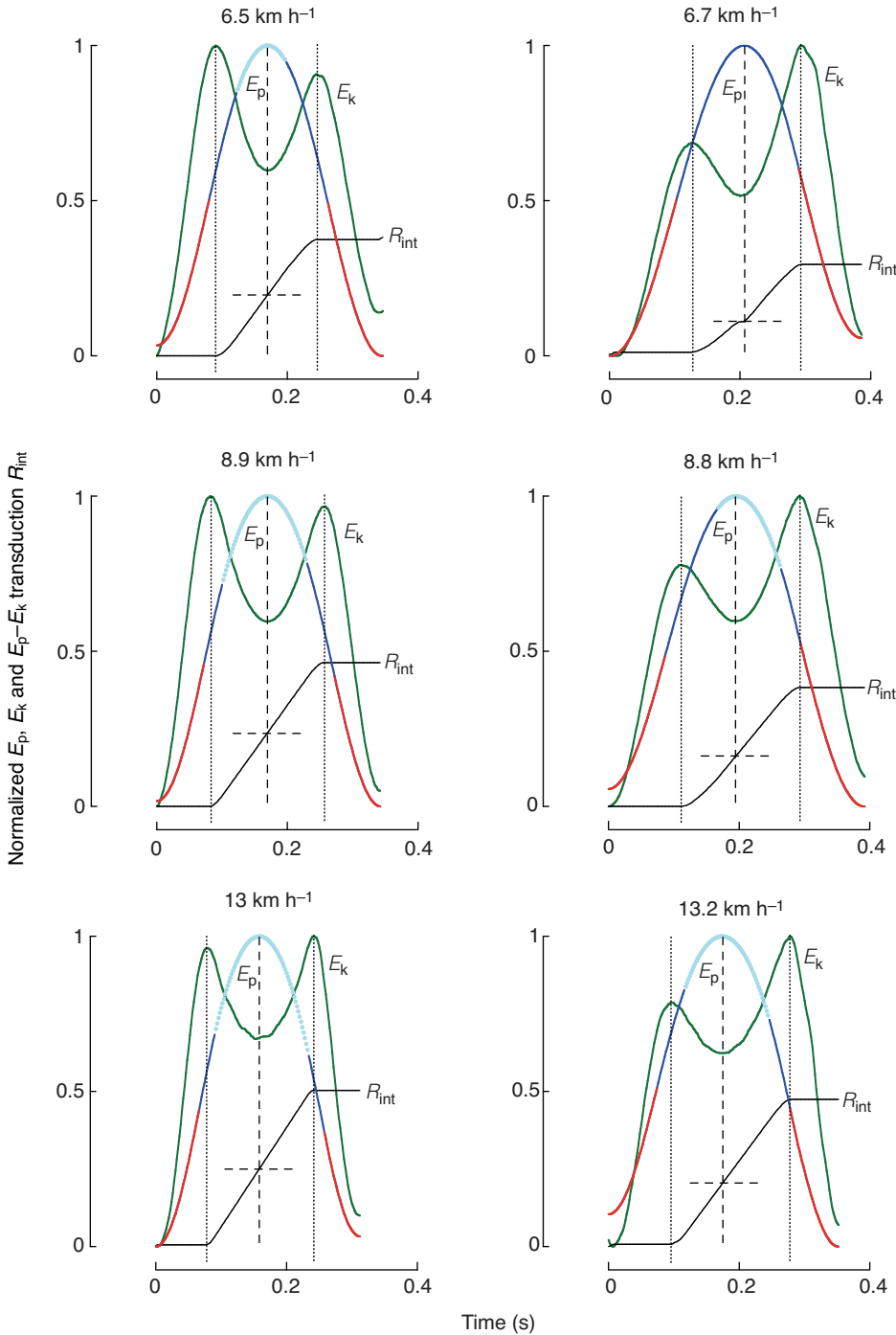


Fig. 4. Same subject as in Fig. 2 (backward running, left; forward running, right). For each speed the  $E_p-E_k$  transduction during one step,  $R_{int}$  (black), is illustrated with the simultaneous changes in kinetic energy,  $E_k=E_{kv}+E_{kf}$  (where  $v$  is vertical and  $f$  is forward; green), and gravitational potential energy,  $E_p$ , normalized to oscillate between zero and one. The colours in the  $E_p$  curve distinguish the fractions of the step where the vertical force exerted on the ground is greater than body weight (red), and lower than body weight (blue). The continuous  $E_p$  line indicates the contact phase whereas the dotted  $E_p$  line (light blue) indicates the aerial phase (not present in the upper right panel). The vertical dotted lines are drawn through the two peaks of  $E_k$  and encompass the fraction of the step where the  $E_p-E_k$  transduction occurs, as indicated by the increment of the  $R_{int}$  curve. Note that  $E_k-E_p$  transduction during the lift (increment of  $R_{int}$  below crossing of the dashed lines) and the final level attained by the  $R_{int}$  curve are greater in backward running than in forward running.

the impulse of the ground reaction force is directed more vertically during the brake than during the push, i.e.  $d_{f,v}/d_{f,h} > a_{f,v}/a_{f,h}$ . Average values obtained from the nine subjects running at a slow, intermediate and high speed are:  $a_{f,v}/a_{f,h} = 0.81 \pm 0.04$  and  $d_{f,v}/d_{f,h} = 0.65 \pm 0.10$  at the slow backward running speed of  $5.06 \pm 0.45 \text{ km h}^{-1}$  versus  $a_{f,v}/a_{f,h} = 0.37 \pm 0.11$  and  $d_{f,v}/d_{f,h} = 0.85 \pm 0.10$  at the slow forward running speed of  $5.08 \pm 0.58 \text{ km h}^{-1}$  ( $N=9$ );  $a_{f,v}/a_{f,h} = 0.85 \pm 0.03$  and  $d_{f,v}/d_{f,h} = 0.74 \pm 0.09$  at the intermediate backward running speed of  $9.17 \pm 0.69 \text{ km h}^{-1}$  versus  $a_{f,v}/a_{f,h} = 0.53 \pm 0.07$  and  $d_{f,v}/d_{f,h} = 0.93 \pm 0.06$  at the intermediate forward running speed of  $9.13 \pm 0.66 \text{ km h}^{-1}$  ( $N=9$ );  $a_{f,v}/a_{f,h} = 0.85 \pm 0.09$  and  $d_{f,v}/d_{f,h} = 0.79 \pm 0.09$  at the high backward running speed of

$14.59 \pm 1.43 \text{ km h}^{-1}$  versus  $a_{f,v}/a_{f,h} = 0.69 \pm 0.08$  and  $d_{f,v}/d_{f,h} = 0.93 \pm 0.03$  at the high forward running speed of  $15.60 \pm 0.97 \text{ km h}^{-1}$  ( $N=9$ ).

#### Vertical stiffness and resonant frequency of the bouncing system

The upper panels of Fig. 6 show the mass-specific vertical stiffness,  $k/M_b = a_{v,max}/S_{ce}$ . It can be seen that in backward running the stiffness is on average greater than in forward running. The bottom panels in Fig. 6 show the resonant frequency of the bouncing system  $f_s = (k/M_b)^{0.5} / (2\pi)$  (dashed lines) together with the freely chosen step frequency  $f = 1/\tau$  (continuous line). In backward running as in forward running the natural frequency of the system  $f_s$  is on average

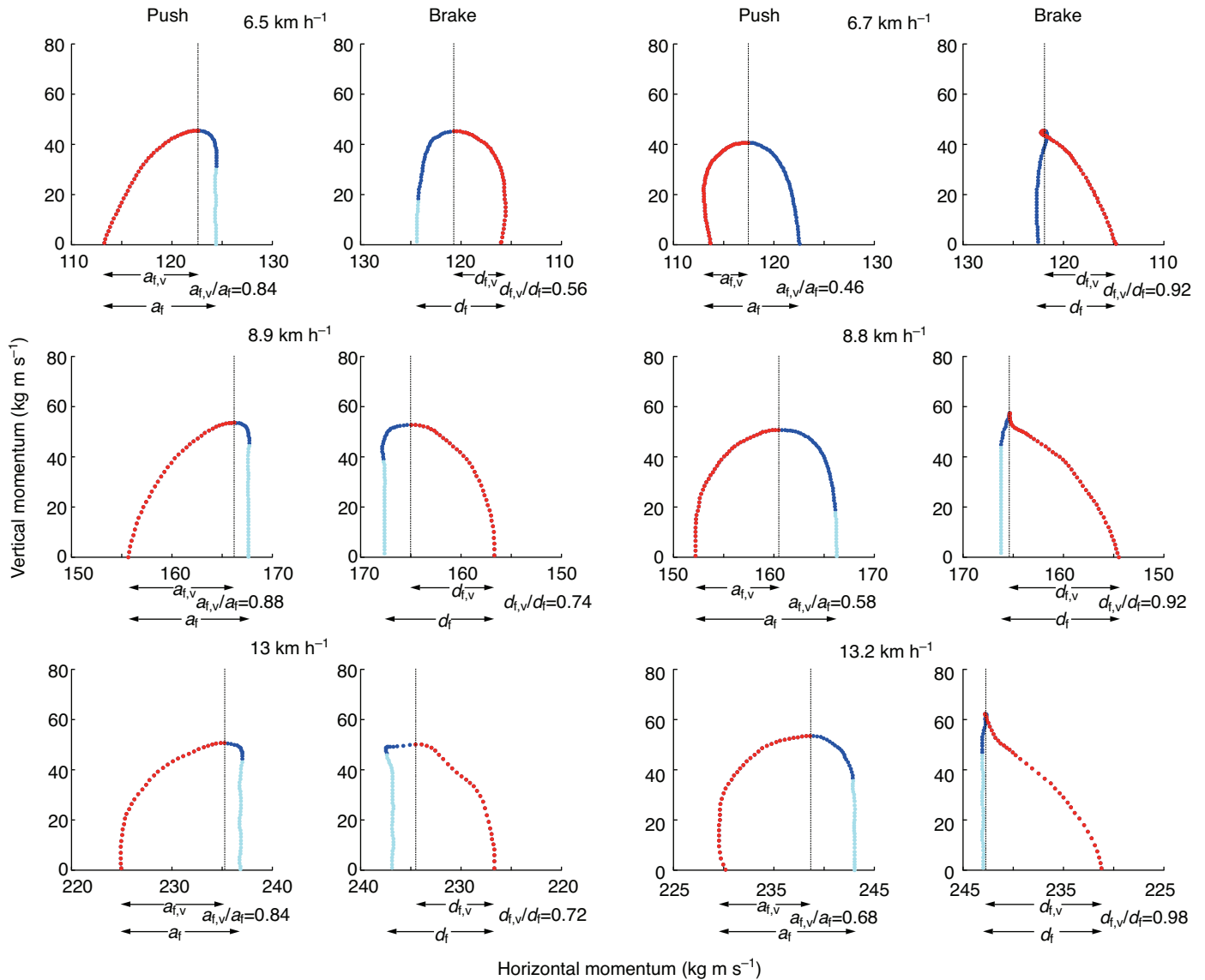


Fig. 5. Same steps and subject as in Fig. 4. The momentum of the centre of mass in the vertical direction,  $M_b V_v$ , is plotted as a function of the momentum of the centre of mass in the forward direction,  $M_b V_f$ , during the push (increment of  $M_b V_f$ ) and during the brake (decrement of  $M_b V_f$ ). Vertical lines are drawn through the maximum value of  $M_b V_v$ . The red section of each plot indicates  $M_b V_v$  changes due to a vertical impulse with a vertical force exerted on the ground greater than body weight, resulting in an increase of  $M_b V_v$  from zero to its maximum during the push and in a decrease of  $M_b V_v$  from its maximum to zero during the brake. The blue section of each plot indicates  $M_b V_v$  changes due to a vertical impulse with a vertical force less than body weight, resulting in a decrease of  $M_b V_v$  during the push and in an increase of  $M_b V_v$  during the brake. The light blue section indicates the aerial phase when  $M_b V_f$  is constant. The fraction of the push during which  $M_b V_v$  increases simultaneously with  $M_b V_f$  is given below each plot by the ratio  $a_{t,v}/a_t$ . The fraction of the brake during which  $M_b V_v$  and  $M_b V_f$  simultaneously decrease is given by the ratio  $d_{t,v}/d_t$ . Note that  $a_{t,v}/a_t > d_{t,v}/d_t$  in backward running whereas  $d_{t,v}/d_t > a_{t,v}/a_t$  in forward running indicating that in backward running, contrary to forward running, the force exerted on the ground is directed more vertically during the push than during the brake.

greater than the step frequency  $f$ . Both  $f_s$  and  $f$  increase with speed more steeply in backward running than in forward running.

**DISCUSSION**

The present study confirms that, at a given speed, the step frequency is higher in backward running than in forward running (Devita and Stribling, 1991; Wright and Weyand, 2001) and that the stance time, i.e. the time of foot contact on the ground ( $t_c$  in Fig. 1) is shorter in backward running than in forward running (Threlkeld et al., 1989; Wright and Weyand, 2001). However, stance time was reported to be the same fraction of stride duration in backward running as in forward running and the vertical impulse given to the body by the

ground reaction force was reported to be smaller in backward running than in forward running, with a shorter flight time explaining the higher step frequency (Threlkeld et al., 1989; Devita and Stribling, 1991). These conclusions are not supported by the present results.

**The vertical push on the ground**

What follows shows that the backward running step is characterized not only by a greater peak vertical acceleration attained during stance  $a_{v,max}$  (Fig. 3) but also by a greater average vertical acceleration and vertical momentum gained during the lower part of the oscillation of the centre of mass.

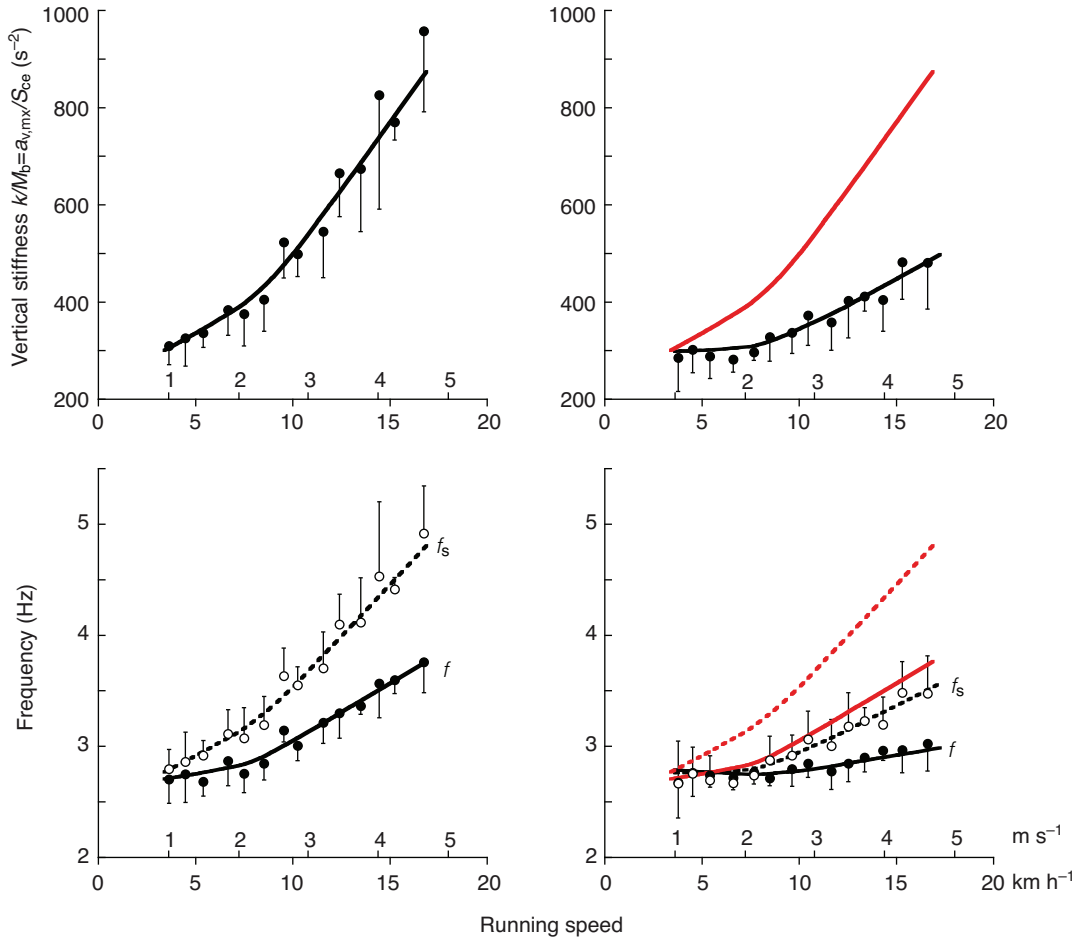


Fig. 6. Left panels: backward running. Right panels: forward running, with backward running lines (red) superimposed for comparison. The upper panels show that the mass-specific vertical stiffness is on average greater in backward running than in forward running. The lower panels show that the step frequency ( $f$ , continuous line) is greater in backward running than in forward running. In both running conditions, the resonant frequency of the system  $f_s$  is greater than the step frequency  $f$  over most of the speed range. Note that  $f_s$  diverges from  $f$  at a lower speed in backward running than in forward running. Statistical analysis as in Fig. 1.

During running on the level, the vertical momentum lost and gained during  $t_{ce}$  (lower part of the oscillation) must equal the vertical momentum lost and gained during  $t_{ae}$  (upper part of the oscillation), i.e.:

$$\bar{a}_{v,ce}t_{ce} = \bar{a}_{v,ae}t_{ae}, \quad (2)$$

where  $\bar{a}_{v,ce}$  and  $\bar{a}_{v,ae}$  are the mean vertical acceleration of the centre of mass during  $t_{ce}$  and  $t_{ae}$ . Fig. 1 (upper right panel) shows that  $t_{ae}$  is on average about equal in backward running and in forward running ( $t_{ae,b}=0.185\pm 0.017$  s versus  $t_{ae,f}=0.186\pm 0.016$  s,  $P=0.659$ ). It follows, from Eqn 2, that the ratio between mean vertical acceleration in backward running,  $\bar{a}_{v,ce,b}$ , and in forward running,  $\bar{a}_{v,ce,f}$ , is:

$$\bar{a}_{v,ce,b}/\bar{a}_{v,ce,f} \approx (t_{ce,f}/t_{ce,b})(\bar{a}_{v,ae,b}/\bar{a}_{v,ae,f}). \quad (3)$$

Eqn 3 shows that the mean acceleration upward during the lower part of the vertical oscillation  $\bar{a}_{v,ce}$  is greater in backward running than in forward running because: (i) as shown in Fig. 1  $t_{ce,f} > t_{ce,b}$  ( $t_{ce,f}=0.172\pm 0.021$  s versus  $t_{ce,b}=0.149\pm 0.026$  s,  $P=1.986\times 10^{-11}$ ), and (ii)  $\bar{a}_{v,ae,b} > \bar{a}_{v,ae,f}$ : in fact the mean acceleration downward during the upper part of the vertical oscillation  $\bar{a}_{v,ae}$  attains the maximum value of  $1g$  during the aerial phase  $t_a$  and the ratio  $t_a/t_{ae}$  is greater in backward running than in forward running ( $t_{a,b}/t_{a,f}=0.531\pm 0.202$  versus  $t_{a,f}/t_{a,b}=0.377\pm 0.251$ ,  $P=1.866\times 10^{-6}$ ).

Rearranging Eqn 3 one can compare the vertical momentum gained during  $t_{ce}$  in backward running and in forward running:

$$\bar{a}_{v,ce,b}t_{ce,b} \approx \bar{a}_{v,ce,f}t_{ce,f}(\bar{a}_{v,ae,b}/\bar{a}_{v,ae,f}), \quad (4)$$

showing that the momentum impressed to the body by the ground reaction force during the lower part of the oscillation is greater in backward running than in forward running because  $\bar{a}_{v,ae,b} > \bar{a}_{v,ae,f}$  as described above.

#### The on-off ground asymmetry of the rebound

The greater vertical momentum impressed on the body in backward running during the lower part of the vertical oscillation of the centre of mass causes a greater duration of the upper part of the oscillation relative to the lower part, i.e. a greater on-off ground asymmetry of the rebound  $t_{ae}/t_{ce}$  ( $t_{ae,b}/t_{ce,b}=1.271\pm 0.184$  versus  $t_{ae,f}/t_{ce,f}=1.097\pm 0.173$ ,  $P=2.105\times 10^{-11}$ ).

Alternatively, according to the more common approach used in the literature, we find that in backward running the aerial time  $t_a$  is increased relative to the contact time  $t_c$  ( $t_{a,b}/t_{c,b}=0.475\pm 0.251$  versus  $t_{a,f}/t_{c,f}=0.296\pm 0.237$ ,  $P=2.502\times 10^{-7}$ ). The greater ratio  $t_a/t_c$  in backward running shows that the stance time  $t_c$  is a smaller fraction of the step period  $\tau$ . A lower  $t_c/\tau$  ratio requires a greater average vertical force exerted during stance to maintain the



average vertical force over the whole step cycle equal to body weight.

Note that  $t_{ae} > t_{ce}$  whereas  $t_a < t_c$  because the duration of the upper part of the oscillation of the centre of mass  $t_{ae}$  includes a fraction of the contact time  $t_c$  (Blickhan, 1989).

In conclusion, the peak vertical acceleration  $a_{v,mx}$  (Fig. 3), the mean vertical acceleration and the vertical momentum gained during the lower part of the oscillation of the centre of mass (Eqns 3 and 4) are all greater in backward running than in forward running with the consequence that the backward running step is characterized by a greater on-off ground asymmetry of the rebound  $t_{ae}/t_{ce}$ .

### The landing-takeoff asymmetry of the rebound

During human running at low and intermediate speeds, as well as in animal hopping, running and trotting, the duration of the brake after landing is shorter than that of the push before takeoff. As during level running at a constant speed the momentum lost equals the momentum gained, the mean force exerted during the brake must be greater than that developed during the push, i.e.  $t_{brake} < t_{push}$  and  $\bar{F}_{brake} > \bar{F}_{push}$  ('hard landing and soft takeoff') (Cavagna et al., 2008b; Cavagna and Legramandi, 2009).

In backward running the landing-takeoff asymmetry is reversed, i.e.  $t_{brake} > t_{push}$  and  $\bar{F}_{brake} < \bar{F}_{push}$  ('soft landing and hard takeoff') (Cavagna et al., 2011). The present study shows that the reversed landing-takeoff asymmetry in backward running is also evidenced by a different trend of the  $E_p-E_k$  transduction during the step ( $R_{int}$  in Fig. 4) and by a different orientation of the ground reaction force during the push and the brake (Fig. 5).

As pointed out in a previous study (Cavagna et al., 2008b), the  $E_p-E_k$  transduction has a different physiological meaning during the downward displacement and during the lift of the centre of mass.

The  $E_p$  into  $E_k$  transduction during the downward displacement can be viewed as a mechanism exploiting gravity to passively increase the vertical downward velocity and as a consequence the kinetic energy. The  $E_p$  into  $E_k$  transduction precedes the negative work phase of the step, provides kinetic energy to be stored within muscle-tendon units during the subsequent brake and requires a high force to decelerate the body downwards. This mechanism applies to forward running as shown by the large increment of  $R_{int}$  during the downward displacement (Fig. 4) and by the finding that almost the entire brake takes place with a ground reaction force having a vertical component greater than body weight (Fig. 5).

The  $E_k$  into  $E_p$  transduction during the lift follows the positive work phase of the step and increases with the push average power developed against gravity before takeoff. In fact, the greater the vertical push the greater the increment in kinetic energy of vertical motion and its subsequent transduction into gravitational potential energy. This mechanism applies to backward running as shown by a large increment of  $R_{int}$  during the lift (Fig. 4) and by the finding that most of the push takes place with a ground reaction force having a vertical component greater than body weight (Fig. 5).

In conclusion, the reversed use of the lever system of the limbs in backward running results not only in the reversal of the muscle groups involved during the brake and the push (Devita and Stribling, 1991) and the reversal of the magnitude of the force and displacement vectors during negative and positive work (Cavagna et al., 2011) but also in the reversal of the  $E_p-E_k$  transduction during the step and in the brake-push direction of the ground reaction force during stance.

### The determinants of the step frequency

The step frequency,  $f = 1/(t_{ae} + t_{ce}) = 1/(t_a + t_c)$ , is greater in backward running than in forward running because of a shorter duration of

the lower part of the oscillation,  $t_{ce}$ , with a similar duration of the upper part of the oscillation,  $t_{ae}$  (Fig. 1). Alternatively, the greater step frequency in backward running can be considered to be due to a decrease of the contact time  $t_c$  (Wright and Weyand, 2001) compensated only in part by an increase of the flight time  $t_a$  ( $t_{a,b} = 0.098 \pm 0.038$  s versus  $t_{a,f} = 0.072 \pm 0.049$  s,  $P = 2.389 \times 10^{-5}$ ). The shorter contact time is probably the consequence of a reduced overall range of motion at the hip and knee joints (Bates et al., 1986).

The shorter duration of the lower part of the oscillation,  $t_{ce}$ , is the expression of an increased vertical stiffness,  $a_{v,mx}/S_{ce} \approx (\pi/t_{ce})^2$  (Fig. 6, upper panels), resulting in a greater resonant frequency of the bouncing system,  $f_s = (a_{v,mx}/S_{ce})^{0.5}/(2\pi) \approx 1/(2t_{ce})$  (Fig. 6, lower panels). In other words, bouncing steps are more frequent in backward running than in forward running because the bounce takes place on a more rigid system.

The increase in stiffness in backward running may be due to the lack of flexion of the knee, usually used in forward running as a shock absorber after landing. The knee joint, already flexed at touch down, maintains a nearly isometric/fixed position during the initial stance phase and extends at the end of the stance phase to propel the body upwards and forwards (Flynn and Soutas-Little, 1993; Devita and Stribling, 1991).

As mentioned in the Introduction of this study, the similarity between the characteristics of backward running hitherto reported in the literature with that of running in old age (a greater step frequency and energy expenditure with a lower vertical ground reaction force and a shorter flight time) suggested a similar mechanism was involved, i.e. a smoother ride at the expense of a greater energy expenditure to reset the limbs more times per minute. The present results show that this is not the case. The average upward acceleration during the lower part of the oscillation never exceeds  $1g$  during running by old men whereas it is greater than  $1g$  in backward running with the consequence that the duration of the upper part of the oscillation is greater than that of the lower part, i.e.  $t_{ae} > t_{ce}$  (Fig. 1), and the step frequency  $f = 1/(t_{ae} + t_{ce})$  is lower than the frequency of the system  $f_s \approx 1/(2t_{ce})$  (Fig. 6). Backward running therefore does not provide as smooth a ride as running in old age, but the higher step frequency may indeed require greater power to reset the limbs more times per minute (Cavagna et al., 2011).

In this study, all of the between-gait comparisons were made at the same absolute speed, i.e. at relatively faster backward running speeds versus relatively slower forward running speeds. If backward and forward running are compared at an equivalent speed, such as the fastest top speed, the conclusions are different. Specifically, the duration of contact on the ground is shorter in backward running than in forward running at the same absolute speed (Fig. 1), but attains the same value in the two conditions at top speed (Weyand et al., 2010). The vertical stiffness is greater in backward running than in forward running at the same absolute speed (Fig. 6), but is possibly similar in the two conditions at top speed as suggested by: (i) the similar contact duration in the two gaits (Weyand et al., 2010) and (ii) the similar natural frequency of the bouncing system  $f_s$  at the highest speeds of backward running in the present study ( $\sim 4.8$  Hz in Fig. 6) and at the highest speeds of forward running in a previous study [ $\sim 5.0$  Hz in fig. 2 of Cavagna et al. (Cavagna et al., 1988)].

### The catapult mechanism in backward running

In a catapult, elastic energy is stored slowly during deformation of an elastic structure and subsequently released rapidly during recoil of the same structure. In spite of losses due to elastic hysteresis, the work returned per unit time, i.e. the power output, is greater than

the power input. As pointed out by Alexander, ‘catapults are power amplifiers’ (Alexander, 1988) and some animals, particularly jumping insects, use the same principle. We think that the catapult principle also applies to backward running, although with some peculiarities and a much lower power amplification than that observed in jumping insects. As in a catapult, and opposite to forward running, the duration of negative work, when muscle–tendon units are stretched and elastic energy is stored, exceeds the duration of positive work, when muscle–tendon units shorten and elastic energy is released [see fig. 2 of Cavagna et al. (Cavagna et al., 2011)]. Because during running on the level at a constant speed the negative work done during the brake equals the positive work done during the push, the difference in brake–push duration translates into a power output during the push greater than the power input during the brake. According to the data collected in a previous study (Cavagna et al., 2011), brake/push power =  $1.157 \pm 0.164$  ( $N=104$ ) in forward running whereas push/brake power =  $1.149 \pm 0.151$  ( $N=107$ ) in backward running. In backward running, however, unlike a catapult, positive work has to be done over a shorter distance than negative work, requiring a greater force for the same amount of work (Cavagna et al., 2011). Furthermore, whereas in a catapult elastic energy is stored and released by the same structure, this is not necessarily the case in backward running. In particular, the extensors of the knee, which are responsible for a large fraction of the power output during the push (Devita and Stribling, 1991), shorten from a state of quasi-isometric contraction without previous stretching (Flynn and Soutas-Little, 1993). In other words, in backward running some energy has to be produced *ex novo* without previous loading.

The described differences in the stretch–shorten cycle taking place during the rebound of the body in backward and forward running have three possible physiological consequences: (i) a greater energy expenditure in backward running due to the lower efficiency of positive work production (Cavagna et al., 2011), (ii) a reduced risk of muscle damage after landing during the brake in backward running because muscle–tendon units are lengthened at a slower rate as a result of the longer duration of the negative work phase, and (iii) enhanced elastic energy storage in forward running as a consequence of the higher force attained during stretching when elastic structures are loaded, whereas the contribution of the contractile component is enhanced in backward running because positive work has to be produced with a greater average force and some of it without previous loading. The forward running mechanism based on elastic energy storage and recovery is more efficient, but subject to a greater risk of muscle fibre damage during fast muscle stretching following impact with the ground, whereas the backward running mechanism is more expensive, less efficient but probably safer.

#### LIST OF SYMBOLS AND ABBREVIATIONS

$a_v$	vertical acceleration of the centre of mass
$a_{v,mx}$	maximal vertical acceleration of the centre of mass
$E_{cm}$	mechanical energy of the centre of mass
$E_k$	kinetic energy of the centre of mass
$E_{kf}$	kinetic energy of forward motion of the centre of mass
$E_{kv}$	kinetic energy of vertical motion of the centre of mass
$E_p$	gravitational potential energy of the centre of mass
$f$	step frequency
$f_s$	resonant frequency of the system
$F_v$	vertical force
$\bar{F}_{brake}$	mean force exerted during the brake
$\bar{F}_{push}$	mean force developed during the push
$M_b$	body mass

$r(t)$	time course of the transduction between gravitational potential energy, $E_p(t)$ , and translational kinetic energy in the sagittal plane, $E_k(t)$
$R_{int}$	cumulative energy recovery resulting from the instantaneous $E_k-E_p$ transduction
$S_a$	vertical displacement of the centre of mass during $t_a$
$S_{ae}$	vertical displacement of the centre of mass during the upper part of the oscillation
$S_c$	vertical displacement of the centre of mass during $t_c$
$S_{ce}$	vertical displacement of the centre of mass during the lower part of the oscillation
$S_v$	vertical displacement of the centre of mass during each step
$t_a$	aerial time
$t_{ae}$	duration of the upper part of the oscillation
$t_{brake}$	duration of the brake
$t_c$	ground contact time
$t_{ce}$	duration of the lower part of the oscillation
$t_{push}$	duration of the push
$V_f$	forward velocity
$V_v$	vertical velocity
$\tau$	step period

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