Running humans attain optimal elastic bounce in their teens

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In an ideal elastic bounce of the body, the time during which mechanical energy is released during the push equals the time during which mechanical energy is absorbed during the brake, and the maximal upward velocity attained by the center of mass equals the maximal downward velocity. Deviations from this ideal model, prolonged push duration and lower upward velocity, have found to be greater in older than in younger adult humans. However it is not known how similarity to the elastic bounce changes during growth and whether an optimal elastic bounce is attained at some age. Here we show that similarity with the elastic bounce is minimal at 2 years and increases with age attaining a maximum at 13-16 years, concomitant with a mirror sixfold decrease of the impact deceleration peak following collision of the foot with the ground. These trends slowly reverse during the course of the lifespan.

Indirect evidence that energy is partly conserved in human running thanks to an elastic bounce of the body is provided by an efficiency of positive work production twice that attained by a contracting muscle1,2. The elasticity of the bounce can also be directly deduced by considering the mechanical energy changes of the center of mass of the body after landing and before takeoff5,6. In bouncing gaits such as running, hopping and trotting, mechanical energy is absorbed each step by muscle-tendon units when the body decelerates during the brake and restored when the body reaccelerates during the push. In this stretch-shorten cycle of muscle-tendon units, some energy is stored elastically during stretching and recovered during shortening. In adult running elastic energy storage and recovery is greater the greater the length change of tendon relative to that of muscle. This is because adult tendon has a very small elastic hysteresis5,6, i.e. the force exerted during shortening is only slightly less than during stretching. Muscle’s stretch–shorten cycle on the contrary exhibits a large hysteresis, i.e. a large energy loss, because it exerts a force during stretching Fstr, which may largely exceed that during shortening Fsho. The relative role of muscle vs tendon involvement during the bounce can be considered as deducing that during running on the level at a constant speed the momentum lost during the brake Fstr tbrake equals the momentum gained during the push Fsho tpush, and since Fstr > Fsho in contracting muscle then tbrake < tpush when muscle instead of tendon lengthens and shortens. The ratio between time intervals during which negative and positive work are done tbrake/tpush would approach unity in an ideally elastic bounce sustained uniquely by tendon (where Fstr = Fsho). The asymmetric response of muscle to lengthening and shortening also explains the difference between maximal downward velocity Vmax,down (higher) and upward velocity Vmax,up (lower) attained by the center of mass during the bounce. In fact, a higher Vmax,down can be passively attained during the fall thanks to gravity relying, for the downward deceleration, on the greater force the muscle is able to afford when lengthening during the subsequent negative work phase (brake). On the contrary, a lower maximal upward velocity Vmax,up is actively attained against gravity by muscular contraction during the positive work phase (push) when the muscle is shortening and is capable of a lower force. This explains why, when muscle operates instead of tendon, Vmax,up < Vmax,down. Therefore, tbrake/tpush and Vmax,up/Vmax,down are greater the more the kinetics and the kinematics of the bounce approach those of an ideal elastic body. Both ratios increase with the active muscle contraction that prevents muscle lengthening and thus favors tendon lengthening. In fact: i) tbrake/tpush is lower at low running speed, when muscle activation is lower, whereas tpush at high speeds, when muscle activation is higher; ii) tbrake/tpush is lower in old humans than in young adult humans associated with a lower force attained during the bounce by the elderly5,7.

It is not known how the running bounce differs from that of an ideal elastic body during growth. In this study we measured tbrake, tpush, Vmax,up, Vmax,down and the vertical acceleration of the center of mass of the body a, during running steps in nine age groups with mean ages ranging between 2.6 and 27.7 years.
Results

Indicative records obtained on two subjects 2.5 years and 15.8 years old, where the difference in results between ages is largest, are shown in Fig. 1. In the younger subject:

1) $t_{\text{brake}}/t_{\text{push}}$ is lower mainly due to a shorter duration of the brake consequent to a sharper decrease of the total mechanical energy of the center of mass $E_{\text{tot}}$ following the aerial phase $t_a$.
2) The peak in kinetic energy of vertical motion $E_{kv}$ (where $M_b$ is the mass of the body and $V_c$ is the vertical velocity of the center of mass of the body) is lower during the lift than during the fall, indicating a lower ratio $V_{\text{max,up}}/V_{\text{max,down}}$.
3) The impact deceleration peak following landing $\alpha_{\text{impact}}$ is much greater than in the older subject, whereas the subsequent ‘active’ peak, roughly simultaneous with the minimum of $E_{\text{tot}}$ and $E_{\text{in}}$, is similar to that of the older subject.

Average values of $t_{\text{brake}}/t_{\text{push}}$, $V_{\text{max,up}}/V_{\text{max,down}}$, and $\alpha_{\text{impact}}$ measured in the nine age groups of the present study are given in Table 1 and plotted as a function of age in Fig. 2. The three last rows in Table 1 (indicated by asterisks) and the open symbols in Fig. 2 refer to $t_{\text{brake}}/t_{\text{push}}$ and $V_{\text{max,up}}/V_{\text{max,down}}$ data obtained in two previous studies in the same speed range. It can be seen that during growth both $t_{\text{brake}}/t_{\text{push}}$ and $V_{\text{max,up}}/V_{\text{max,down}}$ increase to a maximum at 13–16 years whereas $\alpha_{\text{impact}}$ decreases to a minimum at about the same age. The maximal deceleration downward $\alpha_{\text{impact}}$ following collision of the foot with the ground is, on average, ~6 times greater in the 2 years group than in the 16 years group (Table 1). Subsequently the ratios $t_{\text{brake}}/t_{\text{push}}$ and $V_{\text{max,up}}/V_{\text{max,down}}$ which would attain unity in an elastic bounce, decrease and $\alpha_{\text{impact}}$ increases.

Discussion

The mirroring opposite trend of the $\alpha_{\text{impact}}$ curve with the $t_{\text{brake}}/t_{\text{push}}$ and $V_{\text{max,up}}/V_{\text{max,down}}$ curves in Fig. 2 strongly suggests that the impact peak is a relevant factor impeding an elastic bounce. This is reasonable because some of the mechanical energy absorbed and released by the heel pad and other structures during the impact phase is lost prior the beginning of the push, thus decreasing the mechanical energy at disposal for the subsequent positive work phase. The fall in $E_{\text{tot}}$ during $t_{\text{brake}}$ represents the total amount of energy that can possibly be stored elastically. In the example of Fig. 1, the impact duration occupies ~50% of the total fall in $E_{\text{tot}}$ in the 2.5 years old subject and ~24% in the 15 years old subject. It follows that relatively less mechanical energy is left after the impact phase to be stored in muscle-tendon units of the younger subject during the fall in $E_{\text{tot}}$. The mechanical energy lost during the impact phase must be replaced by muscular contraction during the following positive work phase resulting, as described above, in an increased duration of $t_{\text{push}}$, and in a decrease of $V_{\text{max,up}}$, i.e. in a less elastic bounce and a greater energy expenditure. In fact, measurements made in a previous study show that the efficiency of positive work production during running below 11 km h$^{-1}$ is lower in 4.5 years old children than in 21.6 years adults (0.405 ± 0.046 (s.d.), $N = 46$ vs. 0.426 ± 0.036 (s.d.), $N = 67$, $P = 0.014$).

This study draws attention to two points: i) the youngest subjects are more exposed to high-impact collisions, and ii) the impact peak and the similarity to an elastic bounce change during growth.

The first point has practical health implications. It is known that high-impact collision forces are likely to be associated with injuries of the muscular-skeleton system. The present finding, that the impact peak during running is elevated in the youngest subjects requires particular attention.

With regard to the second point it is relevant to consider that the mass-specific vertical stiffness of the running bounce $k/M_b$ decreases during growth to a minimum in the 16 years group to increase again in the 28 years group with the same trend of the impact peak found in the present study. In other words, the step frequency is higher in the youngest, due to the lower dimensions of their body, requires a higher mass-specific vertical stiffness, to cope with the natural frequency of the bouncing system, and this, in turn, causes a higher impact peak and a lower similarity to an elastic bounce. Interestingly, an inverse relationship between $k/M_b$ and similarity to an elastic bounce was also found when comparing running, trotting and hopping animals of different size. In adult humans, the height of the bounce was also found when comparing running, trotting and hopping animals of different size. In adult humans, the height of the bounce was also found when comparing running, trotting and hopping animals of different size.

In human infants and young children, the height of the running bounce was also found when comparing running, trotting and hopping animals of different size. In adult humans, the height of the bounce was also found when comparing running, trotting and hopping animals of different size.

Figure 1 | Mechanical energy and vertical acceleration of the center of mass of the body in one running step of two subjects with lowest and highest similarity to an elastic bounce. (a), 2.5 years, 16.8 kg, 8.8 km h$^{-1}$; (b), 15.8 years, 50.7 kg, 9.4 km h$^{-1}$. $E_p$ is the gravitational potential energy, $E_{kv}$ and $E_{xf}$ are the kinetic energies of vertical and forward motion, respectively, and $E_{tot} = E_p + E_{kv} + E_{xf}$ is the total mechanical energy of the center of mass in a sagittal plane. Horizontal bars indicate push duration ($t_{\text{push}}$; time interval during which $E_{tot}$ increases, red) and brake duration ($t_{\text{brake}}$; time interval during which $E_{tot}$ decreases, blue) separated by the aerial phase $t_a$. After the aerial phase, $E_{tot}$ decreases sharply in the younger subject resulting in a relatively shorter $t_{\text{brake}}$ and higher peak of $E_b$, with a greater vertical deceleration following impact of the foot on the ground. Arrows show that the fraction of $E_{tot}$ lost during the impact peak, and not available to be stored as elastic energy before the beginning of the push, is relatively greater in the younger subject.
Data shown as mean ± SEM. *p < 0.05 (Microsoft Excel for Mac version 11.6.6).

Table 1 | Similarity to an elastic bounce and impact peak at different ages are confronted with those at 16 yr

| Age (yr) | N (male/female) | Mass (kg) | N runs | t brake / push | t push | V brake,up / push | V brake,down | V impact,up | V impact,down |
|----------|----------------|-----------|--------|----------------|--------|------------------|--------------|-------------|--------------|
| 2.6 ± 0.3 | (6/3) | 1.39 ± 1.6 | 45 | 0.28 ± 0.10 | 5.27 ± 0.22 | 0.76 ± 0.08 | 0.02 ± 0.01 | 0.464 ± 0.026 | 0.002 ± 0.0005 |
| 4.2 ± 0.4 | (7/4) | 2.06 ± 1.5 | 85 | 0.72 ± 0.12 | 8.81 ± 0.10 | 0.84 ± 0.01 | 0.002 ± 0.001 | 0.464 ± 0.026 | 0.002 ± 0.0005 |
| 6.1 ± 0.7 | (6/3) | 2.62 ± 2.8 | 83 | 0.77 ± 0.09 | 5.16 ± 0.10 | 0.88 ± 0.01 | 0.002 ± 0.001 | 0.464 ± 0.026 | 0.002 ± 0.0005 |
| 8.0 ± 0.9 | (6/3) | 3.8 ± 2.3 | 78 | 0.70 ± 0.08 | 2.34 ± 0.10 | 0.90 ± 0.01 | 0.002 ± 0.001 | 0.464 ± 0.026 | 0.002 ± 0.0005 |
| 10.0 ± 1.0 | (7/4) | 5.1 ± 2.8 | 72 | 0.78 ± 0.07 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 |
| 12.5 ± 0.2 | (6/3) | 6.8 ± 2.3 | 78 | 0.70 ± 0.08 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 |
| 16.1 ± 0.4 | (6/3) | 8.8 ± 2.3 | 95 | 0.81 ± 0.10 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 |
| 20.7 ± 0.5 | (6/3) | 10.7 ± 2.3 | 93 | 0.80 ± 0.10 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 |
| 27.0 ± 1.2 | (6/3) | 12.0 ± 2.3 | 107 | 0.80 ± 0.10 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 |
| 34.9 ± 1.4 | (3/1) | 12.0 ± 2.3 | 120 | 0.80 ± 0.10 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 |
| 39.8 ± 1.5 | (3/1) | 4.3 ± 2.3 | 61 | 0.60 ± 0.08 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 |
| 73.4 ± 5.3 | (3/1) | 8.8 ± 2.3 | 75 | 0.80 ± 0.08 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 | 0.464 ± 0.026 | 0.002 ± 0.0005 |

Figure 2 | Effect of age on the similarity to an elastic bounce and on the deceleration peak following impact of the foot on the ground. The similarity to an elastic bounce, which is greater the higher the ratios brake/push and v,max,up/v,max,down increases during growth, attains a maximum in the teens and subsequently decreases. This trend is mirrored by an opposite trend of the impact peak following collision of the foot on the ground after the aerial phase. Symbols are average values (Table 1) measured in the present study (filled squares, circles and crosses) and in two previous studies (open squares and circles).

Methods
Measurements were made starting from records of the force exerted by the foot on the ground in vertical and fore-aft directions obtained in a previous study by means of a force-platform. The method of analysis of the force records to obtain the mechanical energy of the center of mass of the body (Fig. 1) has been described in detail previously. Here we used only runs where: i) the ratio between positive and negative work done during the step to maintain the motion of the center of mass was between 0.75 and 1.25; ii) the curves of gravitational potential energy and of the kinetic energy of forward motion were in phase with an energy transfer between them ≤ 10%; iii) warranting the mechanism of running rather than that of walking, and ii) the ratio between the average vertical force in the complete steps used for the analysis and the weight of the body was between 0.97 and 1.03. Analysis was restricted to running speeds less than 11 km h⁻¹ because below this speed the mean vertical acceleration during the push is independent of body size and age. Written informed consent of the subjects and/or their parents was obtained. Experiments involved no discomfort.

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**Author contributions**

M.A.L. suggested to apply the landing-takeoff software*4,13 to the force-platform records obtained in a previous study*5, did most of the software arrangements and of the analysis of the data. B.S. provided the original force-platform records with instructions for their analysis and mechanical efficiency data, did most of the literature search and provided useful suggestions in the preparation of the manuscript. G.A.C. collaborated with software preparation, did some of the analysis of the data and wrote the paper.

**Additional information**

**Competing financial interests:** The authors declare no competing financial interests.

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