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Skyscraper running: physiological and biomechanical profile of a novel sport activity

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Skyscraper running is here analyzed in terms of mechanical and metabolic requirements, both at the general and at the individual level. Skyscraper runners' metabolic profile has been inferred from the total mechanical power estimated in 36 world records (48–421 m tall buildings), ranked by gender and age range. Individual athlete's performance ($n = 13$) has been experimentally investigated during the Pirelli Vertical Sprint, with data loggers for altitude and heart rate (HR). At a general level, a non-linear regression of Wilkie's model relating maximal mechanical power to event duration revealed the gender and age differences in terms of maximum aerobic power and anaerobic energy resources particularly needed at the beginning of the race. The total mechanical power was found to be partitioned among: the fraction devolved to raise the body center of mass $\dot{W}_{\mathrm{STA.EXT}} = 80.4 \pm 2.9\%$, the need to accelerate the limbs with respect to the body $\dot{W}_{\mathrm{STA.INT}} = 4.5 \pm 2.1\%$, and running in turns between flights of stairs $\dot{W}_{\mathrm{TUR}} = 15.1 \pm 2.0\%$. At the individual level, experiments revealed that these athletes show a metabolic profile similar to middle-distance runners. Furthermore, best skyscraper runners maintain a constant vertical speed and HR throughout the race, while others suddenly decelerate, negatively affecting the race performance.

Running uphill on steep emergency stairs, run-up races as they are usually called today, is a rapidly expanding sport performed on the tallest buildings of the planet. Running on stairs has been an interesting motor activity since Rodolfo Margaria's time, when he designed the rapid ascent test to evaluate the individual maximum anaerobic power (Margaria et al., 1966). Only a few studies have previously discussed stair climbing, some of them considering kinetics and kinematics (Mc Fadyen & Winter, 1988; Yu et al., 1997; Larsen et al., 2009) or metabolic aspects of slow walking on stairs, or under particular conditions such as running while wearing firemen robes (O'Connel et al., 1986; Teh & Aziz, 2002). The particular appeal in this new sport discipline resides in the fact that mostly positive work is carried out (Minetti et al., 1994), that the elastic energy storage and the consequent release in running are practically nil at steep gradients, and that the work to increase the gravitational potential energy [the prevalent portion of the external mechanical work (W_{EXT}), needed to accelerate and lift the body center of mass (BCOM)] considerably exceeds the work to move limbs with respect to the center of mass (the mechanical internal work, W_{INT}). Thus, the required metabolic energy (or the metabolic energy rate) has to be strictly proportional to the total mechanical work (W_{TOT} or power) generated by muscles during the ascent, the last being an easy variable to calculate.

Another attractive aspect relates to the presence, in most skyscrapers, of handrails that maximize the muscle mass involved and, consequently, the mechanical/metabolic power of the ascent, conferring the race with a feel of a global, maximal effort as in rowing. Because the duration of the events ranges from a few dozens of seconds to 14 min and runners attend many different races, both anaerobic and aerobic skills are simultaneously required. Thus, the athlete's choice in terms of the sustainable "engine set-point" is crucial to the overall performance, as an excessive initial power could negatively affect aerobic pathway enzymes and jeopardize the rest of the competition.

Run-up races are organized on buildings of very different heights, and they allow to test predictions about the maximum mechanical power sustainable for a given exercise duration (e.g. Wilkie, 1980) in a wide range of performances. This analysis will also provide the "typical" profile of run-up male and female athletes of very different ages in terms of the aerobic and anaerobic resources available.

The aims of this paper are (1) to define a research methodology for this new sport, (2) to measure the physio-mechanical variables of a group of athletes during a real run-up race and (3) to infer from them the climbing strategy, if any. We will introduce the topic, in the following, by reviewing and analyzing world records in this expanding sport activity.

Analysis of world records

As shown in Fig. 1, races have been organized so far in buildings of very different height, ranging from a few dozen meters to the tallest skyscrapers on the planet (KL Tower, Malaysia, 421 m). The event duration ranges from 50 s to about 14 min and the race conditions vary considerably, not just for climatic reasons. In some cases, a short, level approach to stairs is included and the staircase steps, while being quite similar, are not exactly of the same size/geometry in the different buildings. Runners are often divided into groups, to avoid overcrowding the race terrain, and the group size can affect the overall performance. In addition, the stairs' width affects the usage of handrails as pushing aids, and the number of floors implies a different number of "running turns" for the same vertical distance travelled.

As anticipated in the introduction, run-up races appear to be more easy to analyze mechanically than other sports as, for example, level running, because the power to move vertically is expected to be the predominant fraction of the total power needed. In order to consider the most comprehensive list of determinants, though, we modelled the total mechanical power required to complete the ascent as

$$\dot{W}_{\mathrm{TOT}} = \dot{W}_{\mathrm{STA}} + \dot{W}_{\mathrm{TUR}} \qquad [1]$$

i.e. the sum of the power necessary to run up the stairs ($\dot{W}_{\mathrm{STA}}$) and the one related to running in turns between successive flight of stairs ($\dot{W}_{\mathrm{TUR}}$).

The first term is classically partitioned into the external and the internal portion of the mechanical power

$$\dot{W}_{\mathrm{STA}} = \dot{W}_{\mathrm{STA.EXT}} + \dot{W}_{\mathrm{STA.INT}} \qquad [2]$$

$\dot{W}_{\mathrm{STA.EXT}}$ is estimated as

$$\dot{W}_{\mathrm{STA.EXT}} = \frac{mg\Delta h}{\Delta t} \qquad [3]$$

where m, g, Δh and Δt are the subject mass (made equal to 70 kg), the gravity acceleration, the height of the race inside the building (m) and the race time (s), respectively. We disregarded both the vertical and the forward kinetic energy changes of the BCOM because they are assumed not to affect the overall mechanical work, being "buried" in the monotonically ascending curve of the total energy of BCOM when running at very steep gradients (Minetti et al., 1994).

The term $\dot{W}_{\mathrm{STA.INT}}$ reflects the mechanical internal power necessary to accelerate limbs with respect to BCOM (Cavagna & Kaneko, 1977). Normally obtained by processing kinematics data, here, we estimate its real value using a model equation that has been tested previously for gradient locomotion (Minetti, 1998)

$$\dot{W}_{\mathrm{STA.INT}} = mf\bar{s}^2\left(1 + \left(\frac{d}{1-d}\right)^2\right)q \qquad [4]$$

where f is the stride frequency (Hz), $\bar{s}$ is the (diagonal) speed (m/s) on the stairs, d is the duty factor, i.e. the fraction of the stride period at which one foot is in contact with the ground and q reflects the inertia properties of the four body limbs. Depending on the building height, the race time, the reported number of steps and previous data from our group on gradient

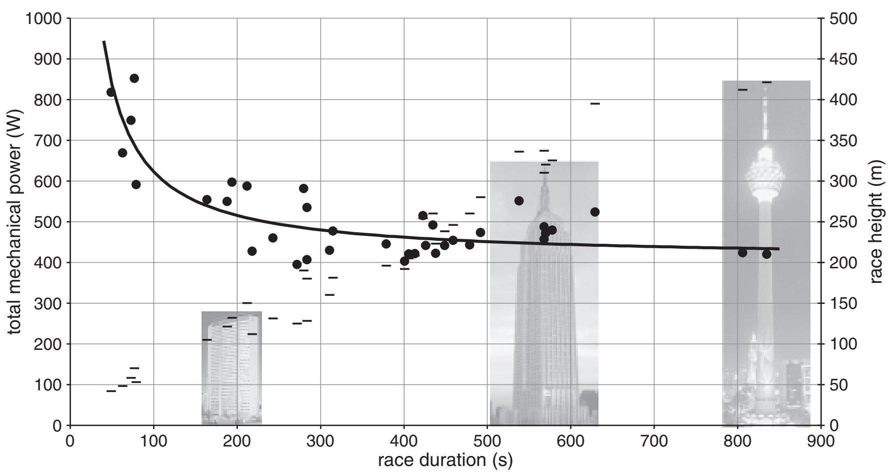

Fig. 1. Current world records of male athletes in run-up races are represented as the "minimum" mechanical power ($\dot{W}_{\mathrm{TOT}}$) needed to set them (solid circles, see text), together with the building height (minus symbols) shown for each record on the right-hand side ordinate, as a function of race duration. The curve represents a non-linear regression of world records ($\dot{W}_{\mathrm{TOT}}$) based on Wilkie's model (see eqn. [5]).

running (Minetti et al., 1994; Minetti, 1998), we estimated for each record f and $\bar{s}$, while d and q were assumed to be equal to 0.45 (extrapolated for a gradient of about 50% from the $\dot{W}_{\mathrm{INT}}$ model) and 0.15, respectively. Stride frequency was deducted from the number of stair steps and from observing that athletes run on every other step, and $\bar{s}$ was estimated by dividing the vertical speed by $\sin(a\tan(i))$, where i is the stairs' gradient (assumed to be equal to the one we measured on the Pirelli building, about 50%).

The mechanical power involved in running in turns between flights of stairs ($\dot{W}_{\mathrm{TUR}}$) and its metabolic energy consumption have never been studied in the past. A set of preliminary experiments provided the metabolic equivalent of $\dot{W}_{\mathrm{TUR}}$ (see Appendix). A curvature radius of 1 m describing the body trajectory to the next floor, as measured on the Pirelli building in Milan, has been assumed for all the buildings involved in world run-up records. Because of this methodological approach, we can expect that estimated $\dot{W}_{\mathrm{TUR}}$ reflects the sum of the external and the internal power of running in circles.

The total mechanical power ($\dot{W}_{\mathrm{TOT}}$) needed to achieve the world records on 36 skyscrapers, calculated according to the above equations, is shown as solid circles in Fig. 1. The prediction is supposed to be reliable due to the expected absence of the elastic energy stored and released during the contact phase (Minetti et al., 1994). In any case, the estimated $\dot{W}_{\mathrm{TOT}}$ and the related metabolic energy consumption, obtained by dividing by the muscle contraction efficiency, represent the "minimum" work rate and energy consumption for each ascent. Additional components of $\dot{V}_{O_2}$ could include, for example, the effect of antagonist muscles, the need to stabilize the trunk during uphill running and the acceleration at the beginning of each flight of stairs.

When the three main components of $\dot{W}_{\mathrm{TOT}}$ are plotted vs race height, as in Fig. 2, it appears that their contribution is quite constant, being $80.4 \pm 2.9\%$, $4.5 \pm 2.1\%$ and $15.1 \pm 2.0\%$ for $\dot{W}_{\mathrm{STA.EXT}}$, $\dot{W}_{\mathrm{STA.INT}}$ and $\dot{W}_{\mathrm{TUR}}$, respectively.

While in the early days run-up participants were amateur runners, more recent records have been established by professionals; thus, $\dot{W}_{\mathrm{TOT}}$ data in Fig. 1 represent performances of top male athletes in the age range 20–35 years who often attend multiple events on skyscrapers with very different heights (and race durations). It is apparent that the total mechanical power generated is much greater for smaller buildings, where the shorter performance allows to exploit more powerful, high-energy phosphate sources.

Wilkie (1980) attempted to capture this phenomenon by proposing an equation predicting the available average mechanical power ($\dot{W}_{\mathrm{MECH}}$ (W) – the same as our $\dot{W}_{\mathrm{TOT}}$) as a function of the event duration [t (s), same as our Δt] with the assumption that

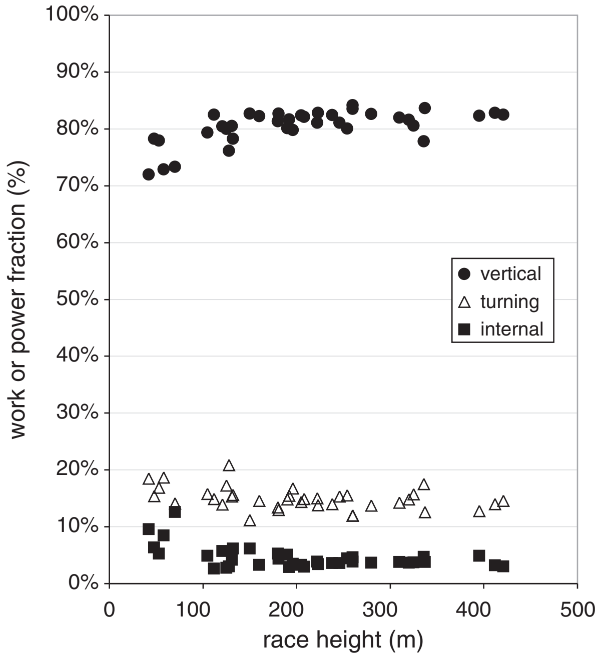

Fig. 2. The three components of the estimated mechanical power (vertical: $\dot{W}_{\mathrm{STA.EXT}}$, turning: $\dot{W}_{\mathrm{TUR}}$, internal: $\dot{W}_{\mathrm{STA.INT}}$, see text) are shown as fractions of $\dot{W}_{\mathrm{TOT}}$, for the different race heights.

subjects reach exhaustion at the end of the exercise

$$\dot{W}_{\mathrm{MECH}} = A + \frac{B}{t} - \frac{A \cdot \tau\left(1 - e^{-\frac{t}{\tau}}\right)}{t} \qquad [5]$$

where A is the maximum long-term mechanical work rate (W), B is the mechanical equivalent of the available energy from anaerobic sources (J) and τ is the time constant (s) reflecting the inertia of the system. Wilkie modelled this equation to be accurate for durations ranging from 40 s to 10 min, which very closely match run-up competitions.

Figure 1 also shows a curve obtained by performing a non-linear regression based on Wilkie's model on the $\dot{W}_{\mathrm{TOT}}$data. The software, written in LabView programming language (downloadable at albertominetti.it/MathModCompMeth), has been tested with mock data series created according to known A, B and τ values. The resulting coefficients were $A = 416.4$ W, $B = 23002.3$ J and $\tau = 5.5$ s.

A and B, once converted into metabolic units according to an efficiency value for muscle contraction of 0.25, define the metabolic profile of this class of athletes. These parameters correspond to the maximum sustainable aerobic power above resting [1.67 metabolic kW or 71.4 ml O_2/(kg min)] for an assumed body mass of 67 kg, in agreement with typical values of middle-distance runners (Saltin & Astrand, 1967) and the anaerobic capacity (92 metabolic kJ, equivalent to 66 ml O_2/kg, a reasonable value indeed for elite athletes), respectively. As mentioned by Wilkie (1980), τ is much shorter than the

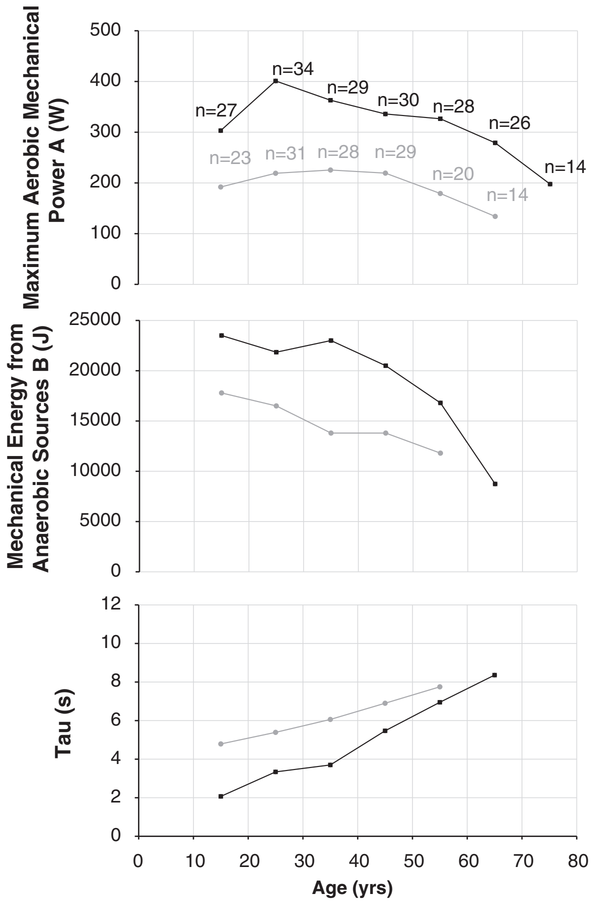

Fig. 3. Effects of age and gender (*n* is the sample size) on the mechanical equivalent of the maximum aerobic work rate, of the anaerobic work capacity and time constant (A, B and τ, respectively, in eqn. [5]), as obtained using non-linear regressions based on Wilkie's model. The *B* and τ values in the oldest age ranges have not been shown because the paucity of records in smaller skyscrapers for those athlete cohorts suggests caution about their reliability.

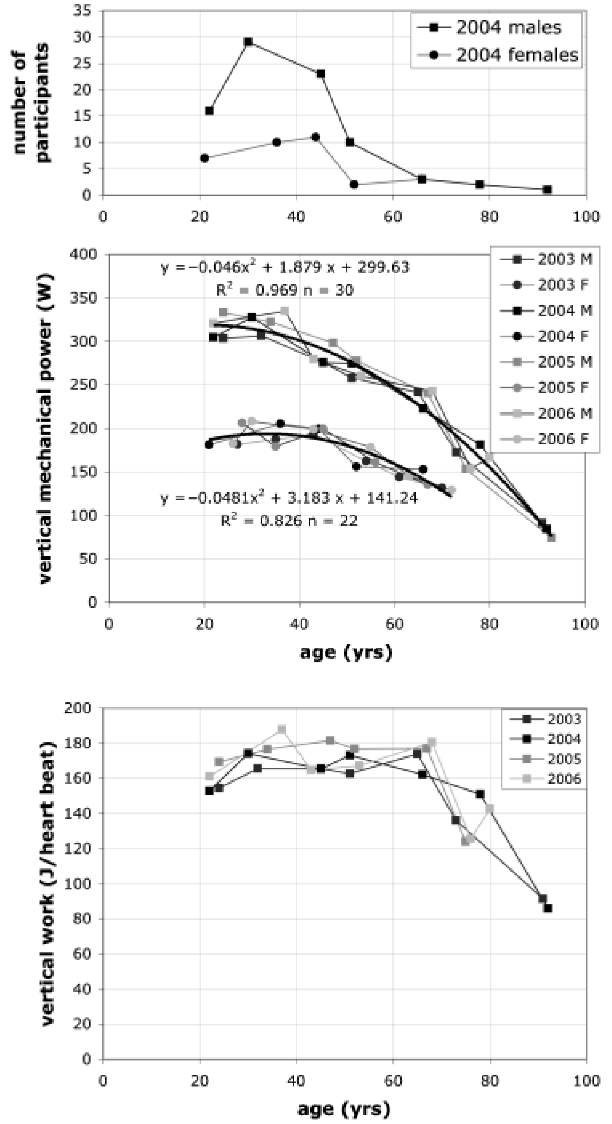

Fig. 4. Upper panel: age distribution of participants of the Empire State Building Run-Up Race held in 2004. Middle panel: vertical mechanical power of female and male winners of run-up races held in four subsequent years. Lower panel: vertical mechanical work per heart beat of male winner of the four run-up races (see the text for details).

time constant of the metabolic transient (typically in the region of 40 s) because it reflects the speed at which the mechanical output increases at the beginning of the exercise.

The analysis of world records also gave us the opportunity to indirectly study the metabolic profile of athletes of different genders and ages. The same non-linear regression applied above on the absolute winners was used on clusters of data pertaining to best male and female athletes (female mass assumed to be 55 kg) within different age ranges categories (from 10 to 80 years, step 10 years). The results are shown in Fig. 3, where the decay of *A* and *B* with increasing age is apparent.

The data scatter observed in Fig. 1 is caused by the heterogeneity of building heights and race features. The variability can be reduced by considering the results from just one race, performed in a given time span. The oldest competition was the Empire State Building Run-Up in New York (320 m height, 1576 steps, 86 floors), which has been running since 1978. Because of the relevant number of male and female athletes of all ages attracted by that race (upper panel of Fig. 4), the variability in terms of event records from 2003 to 2006 (expressed as $\dot{W}_{STA.EXT}$ and shown in the middle panel, Fig. 4) is further reduced. Again, the effect of age is apparent in reducing the available mechanical power. Interestingly, even the oldest participant (aged 91 in 2003) showed worse performances in successive competitions (the three rightmost points for males).

Inferences about the amount of mechanical work sustained by each heart beat (J/beat) as a function of age have been determined by dividing the mechanical vertical power ($\dot{W}_{STA.EXT}$) by the heart rate (HR) (80% of the maximum, estimated according to age, minus the basal value, assumed to be equal to 55 b.p.m.). The lower panel of Fig. 4 shows that up to the age of 65–68 years in males, the work per beat is quite constant, suggesting that the HR could be the most crucial factor in mechanical power reduction with age. The consistent decline for older athletes would imply that other factors, such as the decreases of both the maximum HR and the stroke volume or a lower oxygen extraction, act in combination to reduce the available mechanical power.

Experiments during the Pirelli run-up

As shown in the preceding paragraphs, exercise physiology and locomotion biomechanics provide sufficient information to analyze run-up performance just from record times. These inferences are valid for the average runner, be it a male or a female of a given age. Individual athletes, though, need to be monitored during training and sport events by a proper research protocol. In the following, we describe a simple set of preliminary measurements based on the above analysis of run-ups that we used during a real race.

Methods

The ascent speed of 13 male athletes (see anthropometric data in Table 1), who gave their written informed consent for the experimental procedure, was investigated during the run-up races on the Pirelli building (121 m height, 710 steps, 30 floors) in Milan on February 24 2008 and on March 1 2009. The study was approved by the ethics committee of the University of Milan. Altitude was measured on five athletes using an altimeter+logger device, designed to monitor model aircrafts and rockets, capable of a 0.4 m resolution and a sampling rate of 10 Hz (LoLo/Alti2, Roman Vojtech, http://www.lomcov-ak.cz). The ascent of other four athletes was measured by the internal barometric altimeters of GPSs (Geko 301 and Edge 305, Garmin (Garmin International Inc., Olathe, Kansas, USA)) at a lower resolution (1 m) and sampling rate (1 Hz maximum). Also, HR was monitored during the race (Edge 305 by Garmin; Vantage, RS800 and S810 by Polar, Vantage & Polar, Oulu, Finland). Ascension and HR data of other four elite athletes [including the winner (Thomas Dold) of this and many other run-ups] were provided from their own monitoring equipment after the race.

Lactate was measured (Lactate Analyser YSI Sport, Yellow Spring, Ohio, USA) 3–6 min after arrival in 21 male amateur athletes (mass 68.2 ± 10.0 kg, stature 173.8 ± 6.6 cm, age from 26.5 to 68.6 years) to check their anaerobic status and to estimate the lactate contribution to the work production.

In order to mathematically describe the two-segment shape of the time course of vertical speed observed in many athletes (see "Results"), a statistical algorithm fitting a single data set with two successive regression lines was used (Jones & Molitoris, 1984). The method searches, among all possible two-line combinations, the optimum one in terms of the minimum residuals across the entire data set and statistically assesses whether two lines fit better than a single one. A result that is derived is the optimum breakpoint, i.e. the point in the abscissa (and the corresponding ordinate) at which the second regression line comes into action. The method has been translated into a computer program (LabView, National Instrument, Austin, Texas, USA) and additional features have been added. Because it is expected that points lying on a (concave or convex) monotonous curve are better fitted by two lines than by a single one, we included a subroutine checking to observe whether a second-degree polynomial fits better than two adjacent lines, again based on the minimization of the sum of residuals (a more detailed description and the program is downloadable at albertominetti.it/MathMod-CompMeth). The single line and the second-degree polynomial represent continuous time courses of the vertical speed, while the two-segment model describes a discontinuous performance. While a parabola regression provides three parameters, the two-segment model would involve four of them (two intercepts and two slopes) but, due to the constraint imposed by the intersection, the effective parameters reduce to three, and the adherence of the two models to the same data can be compared.

Results

In the male amateur athletes, the average lactate concentration at the end of the race was 5.3 ± 1.4 mM

Table 1. Antropometric data of the investigated run-up runners are shown in the table, together with the estimated partitioning of their total mechanical power (see text)

Subjects	Age (years)	Body mass (kg)	Stature (m)	Ascent time (s)	Vertical speed (m/s)	$\dot{W}_{STA.EXT}$ (W_{MECH})	$\dot{W}_{STA.INT}$ (W_{MECH})	$\dot{W}_{TUR}$ (W_{MECH})	$\dot{W}_{TOT}$ (W_{MECH})
1	23	69	1.78	188	0.642	435.7	30.663	75.26	541.6
2	22	68	1.79	209	0.579	386.9	22.121	66.85	475.9
3	38	68	1.77	222	0.544	363.6	18.352	62.81	444.8
4	31	60	1.65	255	0.473	279.0	10.647	48.19	337.8
5	28	59	1.64	270	0.447	259.6	8.872	44.85	313.3
6	37	72	1.76	249	0.484	342.8	13.721	59.22	415.8
7	42	77	1.78	258	0.468	354.3	13.239	61.20	428.7
8	28	72	1.52	314	0.384	272.2	6.867	47.02	326.1
9	48	75	1.76	329	0.367	270.6	6.219	46.75	323.6
10	64	69	1.75	335	0.360	244.5	5.419	42.24	292.1
11	58	78	1.67	362	0.333	255.6	4.847	44.16	304.6
12	47	72	1.74	365	0.331	234.1	4.372	40.45	279.0
13	49	53	1.68	428	0.282	147.0	1.997	25.40	174.4

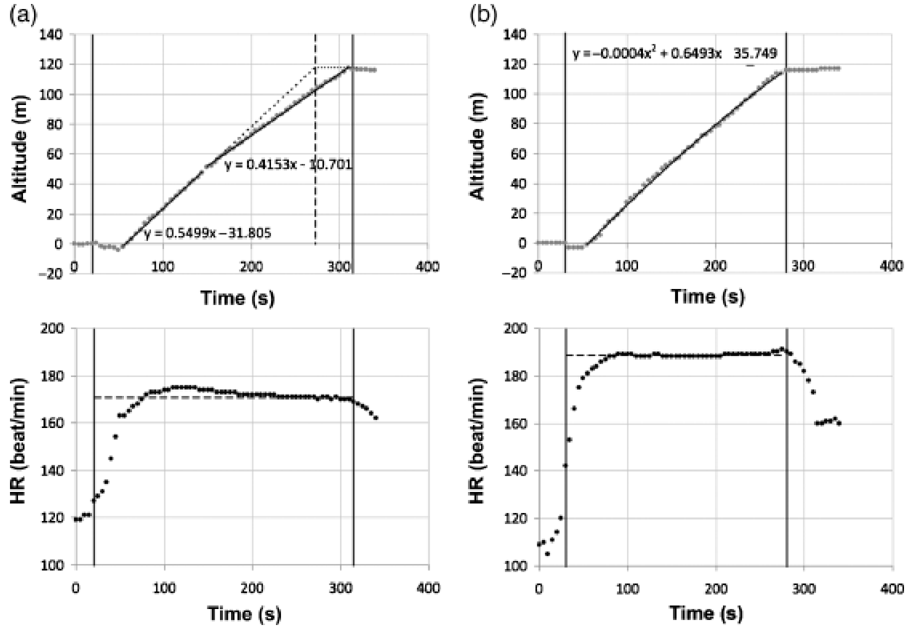

Fig. 5. Two examples of ascent profile and concurrent heart rate time course (upper and lower panels, respectively) are shown for two typical athletes: a discontinuous profile and a very steady ascent (left- and right-hand side, respectively). It can be noted that the discontinuous profile corresponds to a heart rate overshoot that could jeopardize the rest of the race performance.

(range 2.50–7.75), with no significant effect of race speed on it.

Table 1 reports the partitioning of the total mechanical work rate for the 13 individually studied runners according to the rationale described in the introduction ("Analysis of world records"). Nine of them, monitored through digital altimetry during the ascent, showed a sudden change of vertical speed, as significantly detected by the two-segment regression. For eight of them, the change was a reduction of vertical velocity (see an example in Fig. 5, column A), while one subject increased his vertical velocity in the last part of the race. This sudden change was confirmed by the ratio between the residuals related to a second-degree polynomial and the residuals obtained with the two-segment model, which was found to be greater than one in nine cases. Two of these nine athletes showed high ratio values, underlining their considerable speed reduction, as shown by the correlation coefficient of the two-segment model (Fig. 6). In the remaining four athletes, who were the highest in the race ranks for both the under-40 and the over-40 years old categories, this ratio was lower than one, indicating that a continuous function (a line or a parabola), with no abrupt change in vertical speed, better described their uphill motion. This ascent profile index (the residuals ratio) shows an inverse relationship with the average vertical speed in both athlete categories (Fig. 6). When the time of inflection, expressed as a fraction of the individual race time, is plotted against the average vertical speed, a positive trend is apparent (Fig. 7). In synthesis, the more discontinuous ascent occurring in an earlier phase of the race, the worse the overall performance.

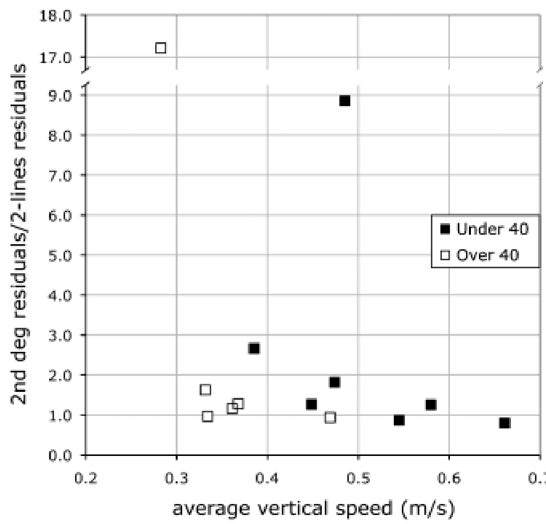

Fig. 6. The ascent profile factor is plotted against the average vertical speed for seven under-40 (solid squares) and six over-40 (open squares)-year-old athletes. The ascent profile factor has been calculated as the ratio between the residuals obtained from using the second-degree polynomial and the ones related to the two-segment regression. The horizontal line located at the value 1 represents the threshold between continuous ascents (below the line) and discontinuous ones (above the line). In both groups, there is a tendency for faster athletes to perform ascents without a sudden vertical velocity change (see text).

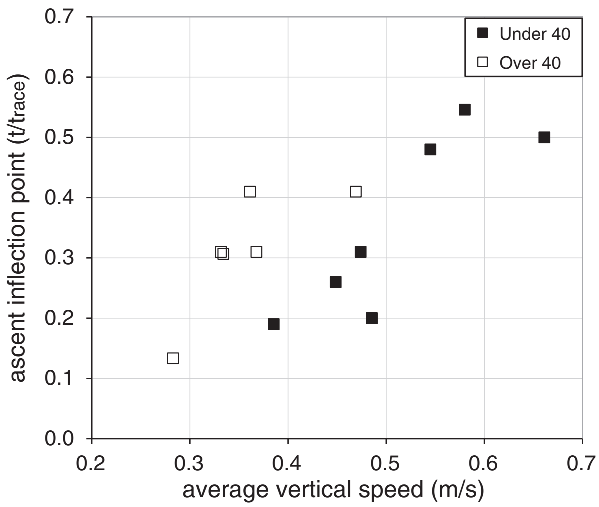

Fig. 7. The ascent inflection time, calculated by the algorithm for the two-segment regression and expressed as a fraction of the total race duration, is plotted against the average vertical speed for seven under-40 (solid squares) and six over-40 (open squares)-year-old athletes.

Discussion

As indicated in the "Analysis of world records" section, the physiology and biomechanics of run-ups are supposed to be quite straightforward. Eighty percent of the total mechanical/metabolic work or power is determined by the increase of body potential energy inherent to ascending upstairs at a gradient of about 50%, the rest being caused by the cost of running in circles between flights of stairs (15%) and by the acceleration of upper and lower limbs with respect to the BCOM (5%). However, different from the high consistency of records of running on a level surface (Minetti, 2004) or run-up records in the same building across many years (Fig. 4), the maximum estimated performance in different buildings, in terms of mechanical work, seems quite scattered (solid circles in Fig. 1). This may be due to building heterogeneity (quoted above), including the variable length of the level approach to stairs, the variable number of floor heights (and number) and the actual vertical distance travelled, which is not always properly reported.

Despite of this variability, which will never be alleviated by race field standardization in this sport, information on the aerobic and anaerobic profile of the competitors can be obtained. The decay of the physiological functional human capacity due to the aging is well known (Tanaka & Seals, 2003). In the present work, published race results, ranked by age ranges and gender, together with the model proposed by Wilkie (1980), allow to show the decay of the (mechanical equivalent of the) aerobic and anaerobic capacity of male and female athletes with age (Fig. 3).

Furthermore, the age-related decline of anaerobic capacity is more pronounced than that of aerobic power, as confirmed recently by Kostka et al. (2009). This evidence partially explains the lower participation of master athletes in short run-up races (less tall skyscrapers).

The results from the present study of the time constant (τ), despite their predictable increase with age in both genders, should be considered with caution. Because Wilkie's model deals with mechanical power, the time constant is only loosely related to the transient on-phase of the "global" oxygen uptake, reflecting preferentially the mechanical and the "local" biochemical transient from rest to maximal exercise levels. Also, Wilkie (1980) warns about the applicability range of his model, from 40 s to 10 min, which almost excludes the influence of the small τ obtained from his study and the present investigation (ranging from 63 to 835 s). The present τ values are even smaller than Wilkie's results, and this could depend on the difference between the two exercise forms: more muscle mass is activated in stair ascending than in pedalling on a cyclo-ergometer. In any case, obtaining τ values much smaller than the shortest event measured suggests that those estimates have to be considered as "extrapolated" results, with little effect on the overall dynamics. However, a mechanical delay in the off–on transient is expected to increase with age, just as it occurs for the on-response time of the oxygen uptake (on average from 25.0 ± 3.4 to 42.0 ± 5.1 s, from 24.2 ± 1.8 to 69.4 ± 1.7 years), (Di Prampero, 2003; DeLorey et al., 2004, 2005; Sabapathy et al., 2004; Gurd et al., 2008).

The reliability of the three model parameters depends both on the number of athletes competing in a given age range (general reliability) and on the attendance to short duration events (B and τ reliability). In this respect, we observed, as mentioned, that old athletes tend not to compete in short run-up races.

Down to the scale of individual athletes, this study shows that a digital altimeter and a HR monitor, both with logging capabilities, are enough to capture and partially explain the race result (the lactate concentration at the arrival was positively but not significantly correlated to the average mechanical power). The time course of the ascent deserves some attention, because many of the investigated runners showed a biphasic profile: the first part of the ascent was performed at a higher vertical speed than the rest of the race, with an abrupt point of inflection (Fig. 5, column A). A more indepth analysis seems to indicate that best runners (higher average vertical speed) show a more uniform ascent profile, without an inflection point (Fig. 6). Also, an early inflection point seems to be negatively related to the overall performance. Only one athlete decided to change his

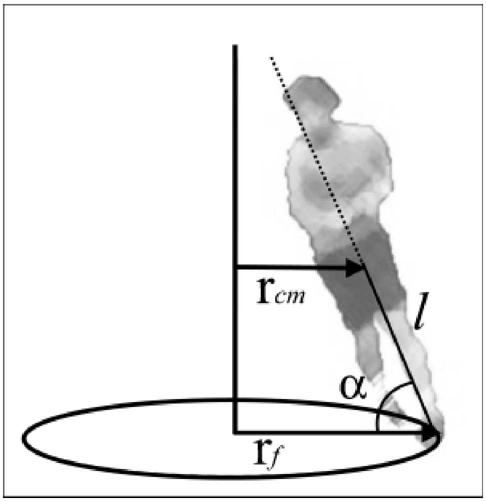

Fig. 8. Sketch of the variables involved in the calculation of leaning angle of the body during running in a circle (see Appendix).

profile in the second half of the ascent, by increasing his velocity. Probably, he saved some energy for the last part of the race, but he did not win the race despite having increased the average vertical speed, underlining our hypothesis that best performance is associated with a uniform ascent profile (Fig. 7).

These observations refer to the individual strategy of conduct during the race. As in many other competitive sports, the final result depends both on the size of the engine and on a proper management of energetic resources during the whole event. It is evident from column B in Fig. 5 how it is possible to climb the building in a shorter time by maintaining a very steady heat rate and mechanical power output (the slope of the ascent profile), rather than starting at a pace that cannot be maintained throughout the entire race (column A).

Our study is the first investigation of this new sport activity; therefore, we cannot draw ultimate conclusions on the true determinants of the observed points of inflection in the ascent profile, which represents an index of power switch, a phenomenon not easily detectable in other sport disciplines. Speculative factors include (1) negative effects of anaerobic metabolism, particularly lactate accumulation and low tolerance, on the aerobic pathways, as partially witnessed by the initial HR overshoot and (2) central or peripheral fatigue, presumably also affecting the propulsive contribution of the upper limbs (lower muscle mass).

Also, it is possible that less experienced athletes tend to initially outperform to gain a leading position in their battery, being convinced that the progression along narrow stairs could be slowed down when moving within a crowd.

These aspects certainly deserve further investigation. The still-limited specialization of athletes and the competition ground heterogeneity, mentioned above, are reflected by the wide scatter of current world records. A strict standardization of ascent characteristics in future run-up events is out of question, but in a few years' time the records of this relatively novel sport activity could display much less variability due to a more focused selection of athletes and more specialized/specific training regimes.

Perspectives

This investigation represents an applied physiology study where a novel motor activity is "dissected" into its metabolic and mechanical aspects and their determinants. Also, the analysis of run-up world records and experiments conducted during two of those races allowed to reach conclusions both at the general and at the individual level.

The novel approach to performance estimation suggests that vertical speed and HR logging are the keys to explain and predict performances in this recent sport discipline, on which there is no scientific literature at present. The developed algorithm to identify the inflection point in the ascent speed could be incorporated, together with a high-resolution digital altimeter, into portable HR monitors. The resulting device would guide athletes during the training sessions and even during races for the optimization of metabolic resources.

Key words: run-up race, mechanical power, digital altimeter, heart rate, aging, Wilkie's Model.

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References

Cavagna GA, Kaneko M. Mechanical work and efficiency in level walking and running. J Physiol 1977: 268: 467–481.

DeLorey DS, Kowalchuk JM, Paterson DH. Adaptation of pulmonary O_2 uptake kinetics and muscle deoxygenation at the onset of heavy-intensity exercise in young and older adults. J Appl Physiol 2005: 98: 1697–1704.

DeLorey DS, Paterson DH, Kowalchuk JM. Effects of ageing on muscle O_2 utilization and muscle oxygenation during the transition to moderate-intensity exercise. J Appl Physiol 2004: 97: 165–172.

Di Prampero PE. Factors limiting maximal performance in humans. Eur J Appl Physiol 2003: 90: 420–429.

Gurd BJ, Peters SJ, Heigenhauser GJ, LeBlanc PJ, Doherty TJ, Paterson DH, Kowalchunk JM. O_2 uptake kinetics, pyruvate dehydrogenase activity, and muscle deoxygenation in young and older adults during the transition to moderate-intensity exercise. Am J Physiol Regul Integr Comp Physiol 2008: 294: R577–R584.

Jones RH, Molitoris BA. A statistical method for determining the breakpoint of two lines. Anal Biochem 1984: 141: 287–290.

Kostka T, Drygas W, Jegier A, Zaniewicz D. Aerobic and anaerobic power in relation to age and physical activity in 354 men aged 20–88 years. Int J Sports Med 2009: 30(3): 225–230.

Larsen AH, Søresen H, Puggaard L, Aagaard P. Biomechanical determinants of maximal stair climbing capacity in healthy elderly women. Scand J Med Sci Sports 2009: 19(5): 678–686.

Margaria R, Aghemo P, Rovelli E. Measurement of muscular power (anaerobic) in man. J Appl Physiol 1966: 21(5): 1662–1664.

Mc Fadyen BJ, Winter DA. An integrated biomechanical analysis of normal stair ascent and descent. J Biomech 1988: 21(9): 733–744.

Minetti AE. A model equation for the prediction of mechanical internal work of terrestrial locomotion. J Biomech 1998: 31: 463–468.

Minetti AE. Passive tools for enhancing muscle-driven motion and locomotion. J Exp Biol 2004: 207: 1265–1272.

Minetti AE, Ardigò LP, Saibene F. Mechanical determinants of the minimum energy cost of gradient running. J Exp Biol 1994: 195: 211–225.

O'Connel ER, Thomas PC, Cady LD, Karwasky RJ. Energy costs of simulated stair climbing as a job-related task in fire fighting. J Occup Med 1986: 28(4): 282–284.

Sabapathy S, Scheider DA, Comadira G, Johnston I, Morris NR. Oxygen uptake kinetics during severe exercise: a comparison between young and older men. Resp Physiol Neurobiol 2004: 139: 203–213.

Saltin B, Astrand PO. Maximal oxygen uptake in athletes. J Appl Physiol 1967: 23(3): 353–358.

Tanaka H, Seals DR. Invited review: dynamic exercise performance in Masters athletes: insight into the effects of primary human aging on physiological functional capacity. J Appl Physiol 2003: 95(5): 2152–2162.

Teh KC, Aziz AR. Heart rate, oxygen uptake, and energy cost of ascending and descending the stairs. Med Sci Sport Exerc 2002: 34(4): 695–699.

Wilkie DR. Equations describing power input by humans as a function of duration of exercise. In: Cerretelli P, Whipp BJ, eds. Exercise bioenergetics and gas exchange. Amsterdam: Elsevier/North Holland, 1980: 75–80.

Yu B, Kienbacher T, Growney ES, Johnson ME, An KN. Reproducibility of the kinematics and kinetics of the lower extremity during normal stair-climbing. J Orthop Res 1997: 15(3): 348–352.

Appendix

Because of the lack of relevant literature on this topic, the metabolic energy consumption involved in running in circles, needed to approximate the total work of skyscraper running, has been obtained by the following procedure.

In two trained male subjects, the relationships between heart rate (HR monitor S810i, Polar, Finland, 1 beat resolution) and oxygen consumption (Vmax, Cardinal Health, USA) were assessed by level running on a treadmill at increasing speed (from 0.8 to 2.8 m/s, step 0.33 m/s). After 8 min of warm-up at slow pace, each speed lasted 4 min, at the end of which measurements took place. The average values of the two variables at all speeds were correlated using a type II linear regression ($R^2 = 0.957$, $n = 7$).

Two weeks later, the same subjects, equipped with HR monitors, underwent an experimental session involving running in circles. On the flat roof of our department, two 1 m radius circles were drawn as to produce a "figure-of-8" path. This was arranged to prevent the inevitable dizziness after a few minutes of running along a single circle. After a period of practicing, subjects were asked to run for 5 min at three speeds, individually selected from preliminary attempts as to involve an HR in the range of 135–170 b.p.m. The stride frequencies during the preliminary tests were measured and later reproduced by a metronome. The tests, preceded by a 15-min warm-up at leisure speed, were repeated three times, 10-min intervals between them.

From the average HRs measured, the corresponding $\dot{V}_{O_2}$ values were estimated according to the $\dot{V}_{O_2}$/HR relationship obtained previously in the laboratory. To calculate the metabolic cost of transport for running in circles, the net $\dot{V}_{O_2}$ was divided by the speed of the BCOM. This speed is lower than the one (of the feet) along the figure-of-8 path according to the different leaning of the body, necessary to counteract the centrifugal effect of running in circles. It can be demonstrated that the relationship between leaning angle (α, deg.), circle radius (r_f, m) and tangential speed along the path (v_f, m/s) is

$$\tan\alpha = \frac{r_f^2 g}{(r_f - l\cos\alpha)v_f^2}$$

where (m) is the average height of the BCOM.

We used an equation graphing software (Grapher, Apple Inc., Cupertino, California, USA) to calculate that at the measured v_f range (1.64–2.49 m/s), as measured, and for an r_f of 1 m, as expected in the transition between stair ramps, α ranged from 78° to 68°. Then, the speed of the BCOM (v_{cm}, m/s)

$$v_{cm} = v_f \frac{r_{cm}}{r_f}$$

where $r_{cm} = r_f - l\cos\alpha$ (Fig. 8), was in the range from 1.37 to 1.79 m/s. Finally, the cost of running in circles with a 1 m radius was found to be almost speed independent, and equal to 283.1 ± 64.1 ml O_2/(kg km). The mechanical equivalent work [J/(kg m)] was obtained by multiplying the metabolic cost by the muscle efficiency (0.25), and expressed as J/(kg floor) by assuming that two half-circles are normally expected to be travelled for each floor of the building.