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A. Belli · J.-R. Lacour · P.V. Komi · R. Candau
C. Denis

Mechanical step variability during treadmill running

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Abstract The present study was designed to study intra-individual step variability measured both on vertical displacement of the body (ΔZ) and on step time (Δt) parameters by means of a kinematic arm and during treadmill running. A group of 17 subjects ran successively at 60%, 80%, 100% and 140% of their maximal aerobic velocity (v_{amax}). The total number of steps analysed was 6116. The absolute ΔZ step variability ($\sigma \Delta Z$) ranged between 5 mm and 21 mm while the absolute Δt variability ($\sigma \Delta t$) ranged between 6 ms and 40 ms. Step variabilities were due to step asymmetry (from 38.5% to 48.5% of the step variability) and to stride variability. For submaximal velocities (60%, 80%, and 100% v_{amax}) both $\sigma \Delta t$ and $\sigma \Delta Z$ were independent of velocity or body dimensions whereas differences between subjects were significant ($P < 0.01$) for $\sigma \Delta Z$. On the other hand, variabilities were significantly increased when velocity was changed from submaximal to the 140% v_{amax} level. Furthermore, at submaximal levels $\sigma \Delta Z$ was linked to the subject's energy cost of running ($P < 0.05$). Therefore, the intra-individual step variability should not be neglected in future studies on mechanical efficiency of running and it is suggested that, to obtain a good accuracy (better than 1%, $P < 0.05$) on mean value and variability of the mechanical parameters, measurements should be performed on at least 32–64 consecutive steps, which corresponds to about 15 to 20 s of running.

Key words Treadmill running · Step variability symmetry · Kinematic arm · Energy cost of running

A Belli (✉) · J.R. Lacour
Laboratoire de Physiologie – GIP Exercice,
Faculté de Médecine de Lyon Sud, B.P. 12, F-69921 Oullins, France

P.V. Komi
Department of Biology of Physical Activity, University of Jyväskylä, Jyväskylä, Finland

P.V. Komi
Département de Réadaptation Médicale – GIP Exercice,
Faculté de Medécine de Saint-Etienne, France

R. Candau
Laboratoire des Sciences du Sport, U.F.R.-S.T.A.P.S.,
Université de Franche-Comté, Besançon, France

C. Denis
Laboratoire de Physiologie – GIP Exercice,
Faculté de Médecine de Saint-Etienne, France

Introduction

To study mechanical variability of running the most commonly used methods are film (or video) analysis and/or force plate measurements. Film/video analysis is a convenient method for recording displacements of various segments and has been used for computing interindividual variability of segment or joint movements during running (Cavanagh et al. 1977; Bates et al. 1979; Vagenas and Hoshizaki 1992). However, due to the considerable amount of work necessary during the digitising process, film/video analysis is often not convenient to study large populations and/or long lasting movements. Furthermore, it has been found that accuracy and noise problems encountered during film/video measurements (Belli et al. 1993) make it difficult to compute precisely the variability of the displacements of the centre of mass of the runner (CM). Force plates have also been intensively used in running for measuring interindividual variability of ground reaction force parameters during the contact phase. Cavagna (1975) has also developed a method to use force plates and photocells for estimating displacements and energy changes of the CM. However, because the long force plates are technically difficult to handle and they are very expensive, it is to be expected that only a few studies (Bates et al. 1983; Nicol et al. 1991) have used them for measurement of several consecutive steps. Therefore, in many reports using film/video analysis and/or force plate measurement, only a single step per running trial has been analysed. In these conditions, the intra-individual step variability during running is difficult to estimate, and although it has been mentioned in some reports (Cavanagh et al. 1977; Bates et al. 1979), it has not yet, to the best of our knowledge, been studied extensively.

A method based on a kinematic arm principle has been developed recently (Belli et al. 1992) for recording the body displacement in the three spatial directions. It has subsequently been applied to vertical CM displacements during jumping (Belli and Bosco 1992) and validated for measurements of CM energy changes in track running (Belli et al. 1993). Application of the kinematic arm during treadmill running made it possible to analyse a large number of steps during many running velocities and on a greater number of subjects. The intra-individual step variability of vertical body displacement was then studied extensively. At the same time the intra-individual variability of step duration was measured. Furthermore, the possibility of performing oxygen uptake and kinematic arm measurements makes it possible to study the relationship between the step variability of vertical displacement and the energy cost of running (C_R).

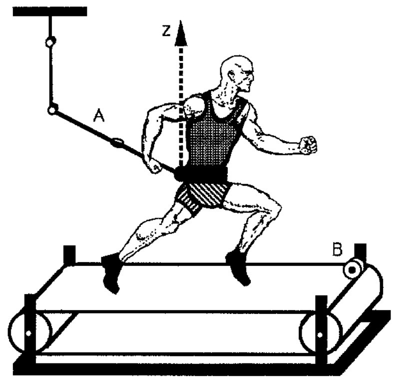

Fig. 1 Side view of the means of measurement. *A* and *B* are the kinematic arm and the encoder wheel measuring the belt displacement, respectively

Methods

Subject and protocol

A group of 17 healthy male subjects, mean age 29.2 (SD 9.8) years, mean body mass 71.6 (SD 8.2) kg, mean height 1.75 (SD 0.07)m, volunteered for this study. They all had training experience in long-distance running or in sprint running and they were also familiar with treadmill running. They were healthy and free of injury or related symptoms at the time of the experiment.

Protocol

The subjects came twice to the laboratory during a 2-week period. The 1st week their maximal aerobic velocity (v_{amax}) was determined. The v_{amax} was calculated from C_R and net maximal oxygen uptake obtained ($\dot{V}O_{2max}$; $ml \cdot min^{-1} kg^{-1}$) during incremental treadmill running. The $\dot{V}O_{2max}$ was determined by a standard open circuit method. The protocol and the methods of collection and measurement of expired gas have been described elsewhere (Lacour et al. 1990). The C_R (Joules per kilogram per metre) at a given velocity (v in metres per second) was calculated as:

$$C_R = \dot{V}O_2 \times EO_2 \times v^{-1} \times 60^{-1}$$

where $\dot{V}O_2$ is the net oxygen uptake and $EO_2 = (21.3 \times (RQ - 0.7)/0.3) + (19.6 \times (1 - RQ)/0.3)$ in Joules per millilitre with respiratory quotient (RQ) given by the ratio of the CO_2 volume produced divided by O_2 volume utilized (Åstrand and Rodahl 1986). Assuming that C_R does not depend on the running velocity (di Pramprero 1986), the mean C_R value $\bar{C}_R$ of 60% v_{amax}, 80% v_{amax} and 100% v_{amax} levels was used for analysis. Furthermore, the relative intra-individual variability of C_R (var C_R) (in percentages) was calculated as follows

$$\text{var}\, C_R = \sigma C_R \times (\bar{C}_R)^{-1} \times 10$$

where σC_R and $\bar{C}_R$ are the standard deviation and the mean of C_R values obtained at 60% v_{amax}, 80% v_{amax} and 100% v_{amax} levels.

The 2nd week, the subjects were asked to run on the treadmill (belt dimensions 0.60 m × 2.40 m) at four constant running velocities corresponding to 60% v_{amax}, 80% v_{amax}, 100% v_{amax} and about 140% v_{amax}. The 140% v_{amax} level refers to the maximal possible running velocity of the subject under treadmill conditions or to the maximal available treadmill velocity (7.1 $m \cdot s^{-1}$), making a high variability for this velocity level. Each trial was maintained for at least 60 s (140% v_{amax}) and for 180 s in most cases (from 60% to 100% v_{amax}). Vertical body displacement and step duration were measured at each running velocity from the 30th to 60th s. All the trials were preceded by at least 10-min rest.

Mechanical measurements

Measurement of vertical body displacement was performed by means of a kinematic arm. The kinematic arm consisted of four light rigid bars linked together by three joints. One end of the kinematic arm was connected to a reference point (reference end) and the other end moved freely in the three spatial directions (moving end). Knowing the bar lengths and the joint angles, the appropriate trigonometric equations could be applied to compute the instantaneous position of the moving end relative to the reference end. The kinematic arm principle and its validation in track running has been described in detail in previous papers (Belli et al. 1992, 1993). To apply the kinematic arm method for treadmill running the reference end of the kinematic arm was fixed to the ceiling while the moving end of the kinematic arm was linked to the subject with a belt fastened around his waist (Fig. 1). Assuming that, as has been reported, the moving end of the kinematic arm follows body displacement (Fenn 1930; Belli et al. 1993), the vertical position (Z) of the body relative to the treadmill belt was computed as follows:

$$Z = l_0 + [l \times cos(a_1)] + [l \times cos(a_1 + a_2)] + [l \times cos(a_3) \times cos(a_1 + a_2)],$$

where l_0 is the vertical distance between the treadmill belt and the reference end of the kinematic arm, l is the length (0.4 m) of the segments of the kinematic arm and a_1, a_2, a_3 are the angles (in radian) of the upper, the middle and the lowest joint of the kinematic arm, respectively. Joint angles were monitored by optical encoders. Under these conditions, it has been shown that the accuracy on position measurement is 1 mm (Belli et al. 1992) and the difference in vertical displacement between the body and CM is 7.6% ± 1.6% (Belli et al. 1993). The instantaneous displacement of the treadmill was measured by means of an extra optical encoder fixed on a wheel mounted on the treadmill belt. The velocity of the treadmill belt was obtained by a first order digital derivation of the displacement signal. As in previous studies the contact was clearly determined by a sudden decrease in the treadmill velocity signal (Cavanagh and Kram 1989). The digital signals from the kinetic arm transducers and from the treadmill displacement transducer were sampled (200 Hz, 12 bits) and stored on a personal computer (386 type). Kinematic arm data were digitally filtered with a 0 phase lag, 2nd order low-pass filter with a cut-off frequency of 10 Hz.

According to Cavanagh and Kram (1989) a step was defined as half a stride (two steps). At each step Z was minimal (Z_{min}) during the contact phase and maximal (Z_{max}) during the following flight phase. In the present paper, the vertical displacement (ΔZ) was the difference between Z_{max} and Z_{min} and the step time (Δt) was measured between two consecutive foot ground contacts. For each subject and each velocity level, ΔZ and Δt were computed for all the measured steps.

Mechanical data analysis

The mean values $\overline{\Delta t}$ and $\overline{\Delta Z}$ of ΔZ and Δt parameters respectively were then computed in each running trial as follows

$$\overline{\Delta t} = \frac{1}{n} \sum_{i=1}^{i=n} \Delta t_i \quad \overline{\Delta Z} = \frac{1}{n} \sum_{i=1}^{i=n} \Delta Z_i$$

where n is the total number of steps analysed and i is the step number. The absolute step variabilities $\sigma\Delta t$ and $\sigma\Delta Z$ of Δt and ΔZ respectively were given by the following computations of the standard deviations:

$$\sigma\Delta t = \sqrt{\frac{1}{n-1} \sum_{i=1}^{i=n} (\Delta t_i - \overline{\Delta t})^2} \qquad \sigma\Delta Z = \sqrt{\frac{1}{n-1} \sum_{i=1}^{i=n} (\Delta Z_i - \overline{\Delta Z})^2}$$

where n is the total number of steps analysed and i is the step number. The relative step variabilities (varΔt and varΔZ) (in percentages) of ΔZ and Δt parameters were calculated as follows:

$$\mathrm{var}\,\Delta t = \sigma\Delta t \times (\overline{\Delta t})^{-1} \times 100 \quad \text{and} \quad \mathrm{var}\,\Delta Z = \sigma\Delta Z \times (\overline{\Delta Z})^{-1} \times 100$$

The data were then smoothed using the following equations:

$$s\Delta t_i = 0.5 \times (\Delta t_i + \Delta t_{i+1}) \quad s\Delta Z_i = 0.5 \times (\Delta Z_i + \Delta Z_{i+1})$$

where $s\Delta t_i$ and $s\Delta Z_i$ are the smoothed values of Δt and ΔZ parameters of step number i, respectively. The mean values ($\overline{s\Delta t}$ and $\overline{s\Delta Z}$) and the standard deviation values ($\sigma s\Delta t$ and $\sigma s\Delta Z$) of the smoothed data were used to calculate the relative stride variability stv Δt and stv ΔZ) (in percentages) and the relative step asymmetry (ass Δt and ass ΔZ) (in percentages) as follows:

$$\mathrm{stv}\,\Delta t = \sigma s\Delta t \times (\overline{s\Delta t})^{-1} \times 100 \quad \text{and}$$

$$\mathrm{stv}\,\Delta Z = \sigma s\Delta Z \times (\overline{s\Delta Z})^{-1} \times 100$$

$$\mathrm{ass}\,\Delta t = \mathrm{var}\,\Delta t - \mathrm{stv}\,\Delta t \quad \text{and} \quad \mathrm{ass}\,\Delta Z = \mathrm{var}\,\Delta Z - \mathrm{stv}\,\Delta Z$$

The contribution of step asymmetry to step variability ($a/v\Delta t$ and $a/v\Delta Z$) (in percentages) was calculated as follows:

$$a/v\Delta t = \mathrm{ass}\,\Delta t \times (\mathrm{var}\,\Delta t)^{-1} \times 100$$

$$a/v\Delta Z = \mathrm{ass}\,\Delta Z \times (\mathrm{var}\,\Delta Z)^{-1} \times 100$$

The present measurement system did not allow us to define clearly which leg (left or right) was acting. However, it was possible to compute, in each running trial, the asymmetry in flexion (FXass) and in propulsion (PRass) as follows:

$$FX\mathrm{ass} = \frac{2}{n} \sum_{i=1}^{i=n/2} (Z_{\min(2i-1)} - \Delta Z_{\min(2i)})$$

$$PR\mathrm{ass} = \frac{2}{n} \sum_{i=1}^{i=n/2} (\Delta Z_{(2i-1)} - \Delta Z_{(2i)})$$

where n is the total even number of step analysed and i is the step number. The "first" leg ($i = 1$) was determined arbitrarily at the beginning of each measurement.

Statistics

Linear regression was used for the statistical analysis of the relationship between $\overline{\Delta t}$, $\overline{\Delta Z}$ and the running velocity and between $\bar{C}_R$ and mechanical parameters. Analysis of variance was used to determine changes of C_R, $\sigma s\Delta t$, $\sigma s\Delta Z$, var Δt, var ΔZ, $a/v\Delta t$ and $a/v\Delta Z$ with running velocity levels. The confidence intervals (corresponding to a given probability of α) on the estimated values $\overline{\Delta t}$ and $\overline{\Delta Z}$ were respective

$$[\overline{\Delta t} \pm (t_{\alpha,n-1} \times \sigma\Delta t \times \sqrt{n}^{-1})] \quad \text{and}$$

$$[\overline{\Delta Z} \pm (t_{\alpha,n-1} \times \sigma\Delta Z \times \sqrt{n}^{-1})$$

where n is the total number of measurements used for the computations of $\overline{\Delta t}$ and $\overline{\Delta Z}$ and $t_{\alpha,n-1}$ is the Student value corresponding to an α probability and an $n-1$ degree of freedom (Renault 1991). The corresponding ranges of error (in percentages) made on the estimated values $\overline{\Delta t}$ and $\overline{\Delta Z}$ were then:

$$\pm t_{\alpha,n-1} \times \sigma\Delta t \times \sqrt{n}^{-1} \times \overline{\Delta t}^{-1} \times 100 \text{ and}$$

$$\pm t_{\alpha,n-1} \times \sigma\Delta Z \times \sqrt{n}^{-1} \times \overline{\Delta Z}^{-1} \times 100$$

which gave finally:

$$\pm t_{\alpha,n-1} \times \mathrm{var}\,\Delta t \times \sqrt{n}^{-1} \quad \text{and} \quad \pm t_{\alpha,n-1} \times \mathrm{var}\,\Delta Z \times \sqrt{n}^{-1}$$

The level of probability was fixed at $\alpha = 0.05$.

Results

The mean maximal aerobic velocity and the energy cost of running of the subjects were 4.86 (SD 0.31) $m \cdot s^{-1}$ and 4.11 (SD 0.17) $J \cdot kg^{-1} \cdot m^{-1}$, respectively. The intra-individual C_R variability was 4.58% (SD 2.76%) and ranged from 0.67% to 10.9%; however, analysis of variance showed that C_R values were not significantly different from 60% v_{amax} to 100% v_{amax}. The respiratory quotients of 60% v_{amax}, 80% v_{amax} and 100% v_{amax} levels were 0.90 (SD 0.03), 0.93 (SD 0.04) and 1.08 (SD 0.04) respectively. Finally the treadmill velocity levels were 2.85 (SD 0.23) $m \cdot s^{-1}$ [59 (SD 1)% v_{amax}], 3.92 (SD 0.28) $m \cdot s^{-1}$ [81 (SD 1)% v_{amax}], 4.93 (SD 0.33) $m \cdot s^{-1}$ [102 (SD 2)% v_{amax}], and 6.77 (SD (0.4) $m \cdot s^{-1}$ [140 (SD 13)% v_{amax}]

Mean values and absolute variabilities of mechanical parameters

Typical instantaneous measurement of vertical displacement and of treadmill velocity are presented in

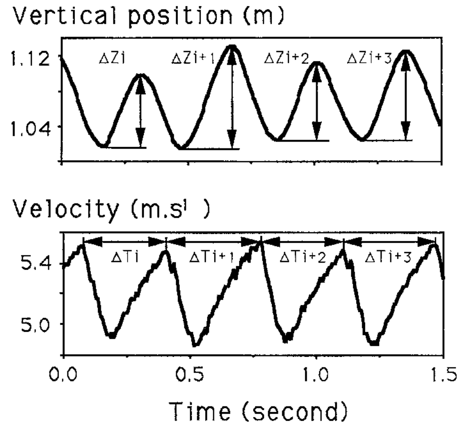

Fig. 2 Typical curves obtained for vertical body displacement (*upper panel*) and treadmill belt velocity (*lower panel*) in regard to running velocity. For clarity only four consecutive steps are shown

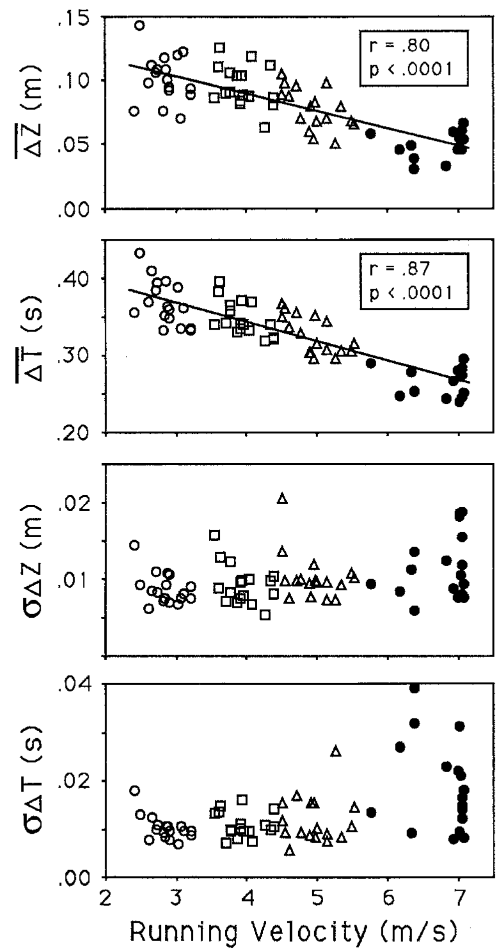

Fig. 3 Mean vertical body displacement ($\overline{\Delta Z}$), mean step duration ($\overline{\Delta t}$), variability of body vertical displacement ($\sigma\Delta Z$) and variability of step duration ($\sigma\Delta t$) in regard to running velocity. *Open dots, squares, triangles* and *filled dots* represent the data obtained for percentages of maximal aerobic velocity of 60%, 80%, 100% and 140%, respectively.

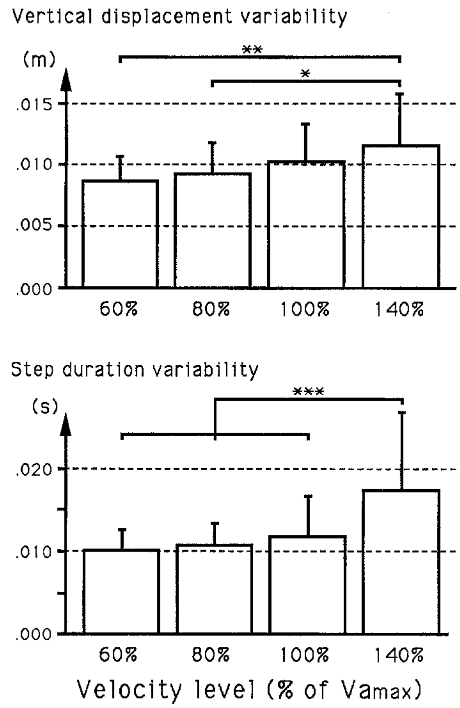

Fig. 4 Absolute variability of vertical body displacement (*upper panel*) and of step duration (*lower panel*) in regard to relative running velocity level (as a percentage of maximal aerobic velocity). v_{amax}, maximal aerobic velocity; significant differences, $*P < 0.05$, $**P < 0.01$, $***P < 0.001$

Fig. 2. The plots of $\overline{\Delta t}$, $\overline{\Delta Z}$, $\sigma\Delta t$, and $\sigma\Delta Z$ obtained at different running velocities and for the 17 subjects are shown in Fig. 3. The values used in these relationships were means or standard deviations of 70–120 steps analysed (depending on step frequency) during the 30 s-periods of each of the 68 measurements performed. The total number of steps analysed was 6116. The $\overline{\Delta t}$ and $\overline{\Delta Z}$ and decreased linearly with the increase in velocity (all $P < 0.001$). The data points were no better fitted using polynomial regressions. Absolute step variability, stride variability and step asymmetry obtained for $\overline{\Delta Z}$ and $\overline{\Delta t}$ parameters and for different velocity levels are shown in Fig. 4. The analysis of variance showed that absolut variabilities were stable [$\sigma\Delta t = 0.011$ s (SD 0.004) s and $\sigma\Delta Z = 0.009$ m (SD 0.003) m] up to a running velocity of 100% v_{amax} while they increased for a running velocity of 140% v_{amax} ($\sigma\Delta t$ increase was significant between all submaximal levels and 140% v_{amax} (all $P < 0.001$) and $\sigma\Delta Z$ increased significantly only when the running velocity was changed from 60% v_{amax} to 140% v_{amax} ($P < 0.01$) and from 80% v_{amax} to 140% v_{amax} ($P < 0.05$)). Interindividual differences were significant ($P < 0.01$) for $\sigma\Delta Z$ but showed only a nonsignificant tendancy ($P = 0.053$) for $\sigma\Delta t$.

Relative variability and asymmetry of mechanical parameters

Relative step variability, stride variability and step asymmetry obtained for ΔZ and Δt parameters and for

Table 1 Relative values of step variability, stride variability and asymmetry for both step duration (Δt) and vertical displacement (ΔZ) parameters as a function of running velocity expressed as a percentage of maximal aerobic velocity

		Running velocity 60%		80%		100%		140%	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Δt	Step variability (%)	2.8	0.7	3.1	0.7	3.7	1.7	7.3	3.9
	Stride variability (%)	1.6	0.3	1.8	0.4	1.8	0.5	3.6	1.7
	Asymmetry (%)	1.1	0.5	1.3	0.6	1.9	1.3	3.7	2.5
ΔZ	Step variability (%)	8.9	3.2	9.8	2.8	13.5	4.2	23.7	8.9
	Stride variabililty (%)	5.2	1.0	5.6	0.8	7.5	1.8	12.0	3.0
	Asymmetry (%)	3.7	2.5	4.2	2.8	6.1	3.6	11.6	6.9

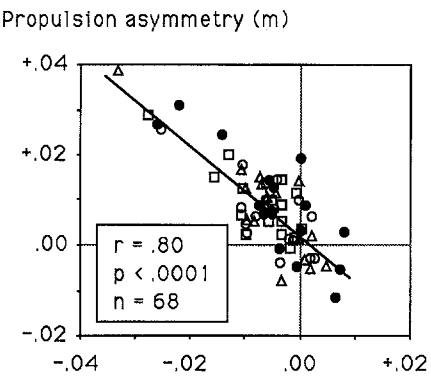

Fig. 5 Relationship between the asymmetry in maximal flexion and the asymmetry in vertical propulsion for two consecutive steps (see Methods). *Open dots*, *squares*, *triangles* and *filled dots* represent the data obtained for percentages of maximal aerobic velocity of 60%, 80%, 100% and 140%, respectively.

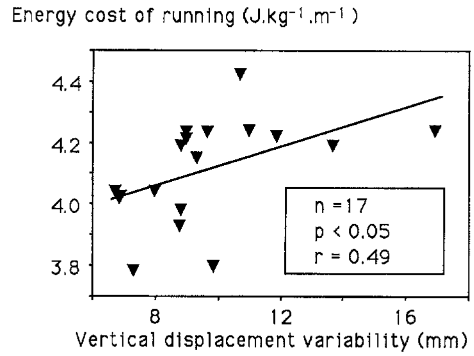

Fig. 6 Relationship between the variability of vertical body displacement and the energy cost of running (average value of the submaximal velocity levels)

different velocity levels are shown in Table 1. The var ΔZ ranged from 5.5% to 37.3% (with 3.5% $\leq$ stv $\Delta Z \leq$ 19.7% and 16.8% $\leq$ ass $\Delta Z \leq$ 23.3%) and the var Δt ranged from 1.7% to 15.6% (with 0.9% $\leq$ stv $\Delta t \leq$ 7.5% and 0.7% $\leq$ ass $\Delta t \leq$ 8.4%). As was the case for absolute variabilities ($\sigma\Delta t$ and $\sigma\Delta Z$) and because Δt and ΔZ decreased with running velocity, analysis of variance showed that relative step variability of both ΔZ and Δt increased clearly ($P < 0.001$) from 100% v_{amax} to 140% v_{amax} (Fig. 3). However, at submaximal levels, var ΔZ and var Δt were stable up to running velocities of 100% v_{amax} and 80 v_{amax} respectively and an increase of var Δt was observed ($P < 0.05$) when the running velocity was changed from 60% v_{amax} to 100% v_{amax}. The contribution (in percentages) of step asymmetry to step variability increased with velocity levels, slightly and not significantly [from 38.5% (SD 11.8)% to 45.5% (SD 12.2)%] for the ΔZ parameter and significantly [from 39.5% (SD 8.2)% to 48.5% (SD 9.4)%, $P < 0.05$] for the Δt parameter. Finally, it was found that the asymmetry obtained, between two successive legs, on maximal flexion was highly negatively related ($P < 0.0001$) to the corresponding difference in vertical propulsion (Fig. 5).

Variability of mechanical parameters and energy cost of running

At submaximal levels, a significant relationship ($P < 0.05$) was found between mean energy cost of running and mean $\sigma\Delta Z$ (Fig. 6). On the other hand, mean C_R was not significantly related to mean values of $\sigma\Delta t$, var ΔZ or var Δt. It was also checked that C_R, $\overline{\Delta Z}$ and $\sigma\Delta Z$ were not correlated with the body height or with the body mass of the subject at any velocity level.

Discussion

Mean values and absolute variabilities of mechanical parameters

The measurements were similar to the values that have been obtained in previous reports (Luhtanen and Komi 1978; Nilsson and Thorstensson 1987). Despite large interindividual differences previously shown on ΔZ (e.g. Luhtanen and Komi 1978; Cavanagh et al. 1985; Williams et al. 1989), the mean amplitude and the changes of ΔZ with the velocity are in agreement with $\overline{\Delta Z}$ values of the present experiment. The present and previous values are therefore comparable, but it must be emphasised that the fast and easy measurement possibilities of the kinematic arm makes the number of steps analysed (6116) in the present study higher than in any previous report and will allow us to discuss the accuracy and the validity of Δt and ΔZ data. Although inter-individual variability of Δt and ΔZ have been often studied (e.g. Nilsson and Thorstenson 1987), to the best of our knowledge, intra-individual $\sigma\Delta t$ and $\sigma\Delta Z$ variabilities have not been published previously. Thus, the present data could provide a basis of comparison for future studies. None of our subjects was perfectly constant and symmetrical in their running patterns but the apparently low variabilities obtained ($\sigma\Delta t = 0.011$ s and $\sigma\Delta Z = 0.009$ m) confirm that, in preprogrammed activities like running, rapid and effective posture and movement control may be achieved in spite of a rather slow neuromuscular apparatus (Rack 1981). At submaximal velocities (from 60% $v_{a\,max}$ to 100% $v_{a\,max}$), $\sigma\Delta Z$ and with less extension $\sigma\Delta t$ values reflected more the interindividual differences than any velocity effect.

Relative variability and asymmetry of mechanical parameters

The ΔZ asymmetry has already been mentioned in many reports (e.g. Cavanagh et al. 1977, 1985), but precise values of ΔZ step variability have not been reported. Regarding the measurement of ΔZ asymmetry, Cavanagh et al. (1977) have taken a slightly different approach by calculating an "index of asymmetry" using the vertical body displacement of two consecutive steps at a running velocity of $4.47\ \mathrm{m \cdot s^{-1}}$. In track conditions, this index was 0.8 and 0.73 respectively for elite and good long-distance runners, corresponding to ΔZ step variability values of 14% and 19% respectively. The values of elite runners were comparable to, while the values of good runners were slightly higher than, the ΔZ step variability of 13.0 (SD 4.8)% found in the present experiment for an equivalent running velocity.

Step asymmetry in kinematics of the lower extremity has also been studied by Vagenas and Hoshiashi (1992) as the preferred velocity of long-distance runners. They have found that most kinematic asymmetries ranged between 4% and 25%, which is compatible with the present data. The ΔZ asymmetry could be the consequence of functional differences between legs (Cavanagh 1990). The fact that a difference between legs in maximal flexion was highly negatively related ($P < 0.0001$) to the corresponding difference in propulsion (Fig. 5) may imply that one leg has a large flexion-extension action while the contralateral leg may act like a "stick' during the support phase. Detailed electromyogram and kinematic analysis of both legs are necessary to validate this hypothesis and to determine whether the stretch shortening cycle plays a role in these differences.

Nevertheless step asymmetry could only explain slightly less than 50% of total ΔZ step variability, and stride variability should be taken into account in variability studies. To the best of our knowledge Δt step variability has not been measured previously, but Bates et al. (1979) have indicated that absolute and relative variability occurred on duration of functional phases determined by ground reaction forces during contact of three consecutive footfalls. The mean variability was 4.98% at a running velocity of $4.47\ \mathrm{m \cdot s^{-1}}$. These values are higher ($P < 0.001$, one group student's t-test) than Δt variabilities measured [3.7% (SD 1.7)%] at comparable velocities in the present experiment. It has been suggested that this slight difference could be due to differences in treadmill and track conditions (Ingen Schenau 1980; Williams et al. 1989). It is worth noting that step variability, stride variability and step asymmetry were always lower in Δt than in ΔZ.

One of the parameters the most affected by Δt is horizontal displacement. Therefore, it seems that a better control is exerted by the runner on horizontal displacement compared to vertical displacement. This could be explained by stricter conditions imposed on variations on antero-posterior displacement of the subject, especially under treadmill conditions. For instance, in the present experiment, a 15.6% Δt step variability corresponded to the step to step antero-posterior displacement of 0.25 m, which was practically the upper limit on a 2.4 m long treadmill. It has been reported that this limitation and the intra-step variation of the treadmill velocity could also affect the kinetic energy changes of the CM of the runner (Ingen Schenau 1980). Therefore it is emphasised that experiments performed during outdoor running could show variability values different from those obtained in the present study.

Variability of mechanical parameters and C_R

The physiological and biomechanical factors affecting C_R have recently been reviewed (Morgan et al. 1989; Bourdin et al. 1993). In unfatigued conditions, intra-individual C_R variations have been shown to vary between 2% and 11% for a given speed, probably because of biological errors (Morgan et al. 1989). The interindividual variations of C_R obtained at the three different velocities of the present experiment were in the same range (from 0.67% to 10.9%) and the measured respiratory quotients were close to those obtained in a steady state by Åstrand and Rodhal (1986). Furthermore, no statistical C_R differences were found between the different velocities. Therefore averaging C_R values could also reduce biological errors. For instance, considering each velocity level separately, C_R was not correlated significantly with $\sigma\Delta Z$ (only nonsignificant tendencies, $P < 0.1$, were found at the 60% and 80% levels). In contrast, the inter-individual $\sigma\Delta Z$ differences were

Table 2 Range of error (%) on the estimated mean ($P = 0.05$) according to the variability of the measured parameter and of the number of steps averaged.

	Number of averaged steps							
	2	4	8	16	32	64	128	256
1% Variability	8.99	1.59	0.83	0.53	0.35	0.25	0.17	0.12
2% Variability	18.0	3.18	1.67	1.07	0.69	0.49	0.35	0.25
4% Variability	35.9	6.36	3.35	2.13	1.39	0.98	0.69	0.49
8% Variability	71.9	12.7	6.70	4.26	2.77	1.96	1.39	0.98
16% Variability	144	25.5	13.4	8.52	5.54	3.92	2.77	1.96
32% Variability	288	50.9	26.8	17.0	11.1	7.8	5.54	3.92

related to the differences in mean values of C_R ($P < 0.05$). However this relationship could explain only 25% of C_R differences. In fact, few biomechanical variables have been shown consistently to account for a substantial portion of variation in economy (Morgan et al. 1989). For the same sex, but for a large range of age and body dimensions, body height and especially body mass have been found to influence C_R (Bourdin et al. 1993). However, this was not the case in the present study, probably because of the anthropometric homogeneity of the runners. Furthermore, the fact that $\overline{\Delta Z}$ and $\sigma\Delta Z$ were not correlated with body height or with body mass emphasises the fact as has been shown, that anthropometric variables are not the primary determinant of preferred mechanical patterns (Cavanagh and Kram 1989). It seemed also that the mechanical work or power does not satisfactorily explain the variations in C_R (Morgan et al. 1989). Assuming that ΔZ is connected with potential CM work, additional support for this observation is provided in the present experiment by the lack of relationship further observed between C_R and $\overline{\Delta Z}$ at any submaximal velocity level. Nonetheless, it would be of interest in future studies to correlate C_R with kinetic CM work and with total mechanical work, averaged over a large number of steps.

Methodological consequences of step variability

During running, the error made when calculating the mean value of a step parameter depends on the relative step variability of the considered parameter and of the number of steps measured (see Methods). Bates et al. (1983) have suggested that, when analysing ground reaction forces, mean values from 8 steps are necessary to obtain reliable data in most cases. According to Table 2, mean values obtained with 8 steps have an acceptable accuracy only where the variability of the studied parameter is low (less than 4%). This low variability was measured on the Δt parameter in the present study. Therefore, mean values of Δt and derived parameters (i.e. stride length, stride frequency, time of different phases of running cycle) obtained with few steps seem to be acceptable at least at submaximal running velocities. On the other hand, this error could be as high as 288% when the variability of the parameter is 32% and when only 2 steps are measured. As a consequence, the accuracy of ΔZ and its related parameters (e.g. potential CM work and potential CM power) obtained on a few steps seems to be questionable. This inaccuracy could be another explanation for the poor relationships obtained previously between running economy and mechanical parameters (e.g. Williams and Cavanagh 1987). It is therefore suggested that mechanical parameters should be measured on at least 32–64 steps, which correspond to about 15 to 20 s of measurement. This is the same minimal time period as usually recommended for gas collection when measuring $\dot{V}O_2$ during steady-state levels (Shephard 1992).

Conclusion

Measurements obtained on 6116 steps showed that step variabilities were consistent and due to step asymmetry and to stride variability. The $\sigma\Delta t$ and $\sigma\Delta Z$ were, at least for submaximal velocities, independent of a velocity effect or of body dimensions, whereas interindividual $\sigma\Delta Z$ differences were significant. Furthermore, $\sigma\Delta Z$ was linked to the C_R. Therefore, the intra-individual step variability should not be neglected in future studies on mechanical efficiency of running and it is suggested that mechanical measurements should be performed on at least 32–64 consecutive steps, which correspond to about 15 to 20 s of running.

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