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ORIGINAL ARTICLE

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The use of treadmill ergometers for extensive calculation of external work and leg stiffness during running

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Abstract Recently, new treadmill ergometers have been designed to measure the ground reaction forces during numerous successive steps. From ground reaction forces measured in track running, it has been shown to be possible to compute external mechanical work (W_{ext}) and leg stiffness (k) of a bouncing spring-mass system. However, to the best of our knowledge, there is still no study reporting the inter-stride coefficient of variation (CoV) of W_{ext} or $k$parameters calculated from many successive steps. The aim of this experiment was to investigate the intra-and inter-individual variations of W_{ext} and k while running at different speeds on a treadmill ergometer. Thirteen healthy runners ran at 12, 14, 16 and 18 km h^{-1} during 3 min. Ground reaction forces were measured and recorded during the last 20 s of each exercise (50–62 steps). From these forces, average values and CoV of W_{ext} and k were calculated. W_{ext}significantly increased while k decreased with speed (both $P<0.001$). The mean values of these parameters were in agreement with data already reported and the CoV was less than 6% for all the parameters, showing almost no variation with speed. Therefore, this method of calculation, based on the extensive measurements of ground reaction forces, can be used to extensively study the mechanical parameters of treadmill running, and especially the inter-stride variability.

Keywords Mechanical work · Kinetic work · Dynamic · Ground reaction force

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Introduction

Ground reaction forces as well as the external mechanical work (W_{ext}) done by the centre of mass (CM) and leg stiffness (k) regulation have been widely used to investigate the biomechanics and energetics of running (e.g. Cavagna1975). For instance, it has been shown that the inter-individual differences of the energy cost of running could be related to the corresponding variations of W_{ext} (Bourdin et al. 1995) and of k (Dalleau et al. 1998). For each step,W_{ext} is the sum of the potential work (W_{pot}), which is the work done to raise the CM, and of the kinetic work (W_{kin}), which is the work done to accelerate the CM in the horizontal direction. There are two main methods described in the literature to compute W_{ext}. The reference method measures the ground reaction forces (GRF) of the foot during each step (Cavagna1975) and computes the speeds and displacement of the CM by simple and double time-integration respectively of the GRF.

Another modelling system for human running is based on a spring-mass system in which the system's mass is assumed to be equal to the runner's mass. The spring and its $k$characterise the elastic behaviour of the leg during running (Farley and Gonzalez1996).

Nevertheless, due to both the cost and the limited dimensions of force-plates, it is difficult to record sufficient steps to accurately characterise the mean CM behaviour during running. More, it has been shown that a limited number of steps analysed potentially leads to errors due to the inter-stride coefficient of variation (CoV), which has been reported to be as high as 12%, for instance for the vertical displacement of the CM (Belli et al. 1995).

Recently, the use of a treadmill ergometer allowed the measurement of 3-D GRF during numerous strides while running (Kram et al. 1998), thus avoiding the bias induced by insufficient data. Kram et al. (1998) integrated the GRF signal to calculate the mechanical impulses but there is a lack in the literature concerning the measurement of the CoV of W_{ext} and stiffness in running.

Thus, the aims of this study were to apply the previous studies of Cavagna (1975) and Farley and Gonzalez (1996) to determine the mean values of the external mechanical work and the stiffness of the system, and to quantify the CoV of these parameters (Belli et al. 1995) during running at different speeds on a treadmill.

Methods

A treadmill ergometer (ADAL 3DC, HEF-Tecmachine, France) was used to measure the 3-D GRF during running bouts. Using the same calibration procedure as Belli et al. (2001), the treadmill's static non-linearity was determined to be less than 0.5% and 1% in the vertical and horizontal directions respectively. The natural vibration frequency (when the treadmill was hit with a hammer) was 147 Hz in the vertical direction and 135 Hz in the anterior-posterior and medio-lateral directions.

From the GRF measurements the method described by Cavagna (1975) was applied to the treadmill ergometer as follows. During contact, the vertical acceleration (a_v) was calculated as $a_v = (F_v/m) - g$, where m is the subject's body mass (in kg) and F_v is the vertical GRF (in N). The a_v was integrated twice to obtain the vertical displacement of the CM (Fig. 1). Finally, the potential work done to raise the CM (in Joules) was calculated by multiplying the vertical displacement by the subject's body weight. The horizontal speed of the CM was determined by integrating the mean anterior-posterior (AP) acceleration (which was the AP force divided by the subject's body mass) over the step to obtain the instantaneous changes of the horizontal speed of the CM relative to the ground. Then, the horizontal speed of the CM relative to the treadmill belt was calculated by adding the horizontal speed of the CM to the speed of the treadmill. From this curve, the maximal (v_{max}) and minimal (v_{min}) speeds were extracted (Fig. 1). The kinetic work done to accelerate the body forward (in Joules) was then calculated as $W_{kin} = 1/2\ m\ (v_{max}{}^2 - v_{min}{}^2)$. Finally, assuming that no transfer occurred between kinetic and potential energies in running (Cavagna et al. 1964) and that the medio-lateral work was negligible (Cavagna1975), W_{ext} was the sum of W_{kin} and W_{pot}.

The leg stiffness (k, in kN m^{-1}) was calculated as the ratio of maximal vertical force (F_{max}) to the maximal leg spring compression (ΔL), both occurring at mid-stance (Farley and Gonzalez1996). Leg compression was calculated from the vertical displacement of the CM (Δz), horizontal speed (s), contact time (t_c) and the leg length (L_0):$\Delta L = \Delta z + L_0 - \sqrt{L_0^2 - \left(\frac{1}{2}st_c\right)^2}$. L_0 was determined from subject's height as $L_0 = 0.53\times$ height (Winter 1979).

Thirteen healthy trained runners [age: 26 (5) years, body mass: 63 (5) kg, $\dot{V}O_{2max}$: 63 (4) ml min^{-1} kg^{-1}, mean (SD)] volunteered for this experiment, which was accepted by the local ethics committee. All the subjects were habituated to treadmill running by at least one bout of 10 min of running at different speeds the week before the experiment.

Subjects were asked to run on an instrumented treadmill ergometer (ADAL 3DC, HEF-Tecmachine, Andrézieux-Bouthéon, France). The subjects performed four running bouts at different speeds: 12, 14, 16 and 18 km h^{-1} (respectively 3.33, 3.89, 4.44 and 5 m s^{-1}). The first three speeds were randomly proposed and the last speed was always 5 m s^{-1}, in order to avoid the possible fatigue that could have occurred at such a running intensity. Each running bout lasted 3 min. GRF were sampled during the last 20 s at a frequency of 500 Hz. The GRF were then normalised relative to the duration of each stride, which was defined as the time elapsed from a heel strike to the next ipsolateral heel strike. The mean ($\bar{x}$) and standard deviation (SD) of the stride frequency, works and stiffness were calculated from 50–62 consecutive steps measured at each speed and for each subject. Then, the variability of each parameter investigated was assessed for each subject by calculating CoV as SD/$\bar{x}$.100. Last, the GRF were stride-averaged to obtain mean curves for each subject in each condition then the mean and SD of the whole group were calculated for each parameter.

Statistical analyses were conducted using a two-factor (steps × speed) ANOVA for repeated measurements. The Scheffe's post hoc test was retained. Significance was accepted for $P < 0.05$.

Results

Typical forces, speeds and vertical displacement curves obtained for a subject running at 12 km h^{-1} are displayed in Fig. 1. Mean, between-subject standard deviation and CoV of mechanical parameters are shown in Tables 1 and 2. The $W_{kin}$and W_{ext} increased while k decreased ($P < 0.001$ for all speeds). W_{pot} remained unchanged with the speed. The CoV of stride frequency, works and stiffness was not influenced by the running speed, except for the variabilityof W_{ext}, which exhibited a significant reduction between 12 and 18 km h^{-1}($P < 0.01$).

Discussion

The patterns and amplitudes of the GRF were in agreement with the literature (e.g. Cavagna1975; Kram et al. 1998). The observed values for Wext and its components (W_{kin} and W_{pot}) were also in agreement with those reported by Cavagna et al. (1964). In addition, the fact that W_{ext} and W_{kin} increased linearly with speed is also well documented in the literature (e.g. Cavagna et al. 1964) who observed similar variations. Although W_{pot} was relatively stable, W_{kin} was reported to increase along with the speed (Cavagna et al. 1964). However, the low number of steps analysed (1 per subject) combined with the few subjects included in this study have limited the accuracy of the values given by Cavagna and colleagues (1964; 1975) since it has been demonstrated by Belli et al. (1995) that a minimal number of 8–16 steps needs to be averaged to obtain a good estimate of the mechanical characteristics of a stride. Thus, the present values, calculated from at least 50 steps per condition and per subject, should be more representative of the mechanical parameters of running.

The values of stiffness were also consistent with the data reported by Ferris et al. (1998) or Blickhan (1989) for similar speeds, and taking the differences in speed into account, with the data of Farley and Gonzalez (1996).

To the best of our knowledge, this is the first time that the inter-stride CoV of both stiffness and mechan-

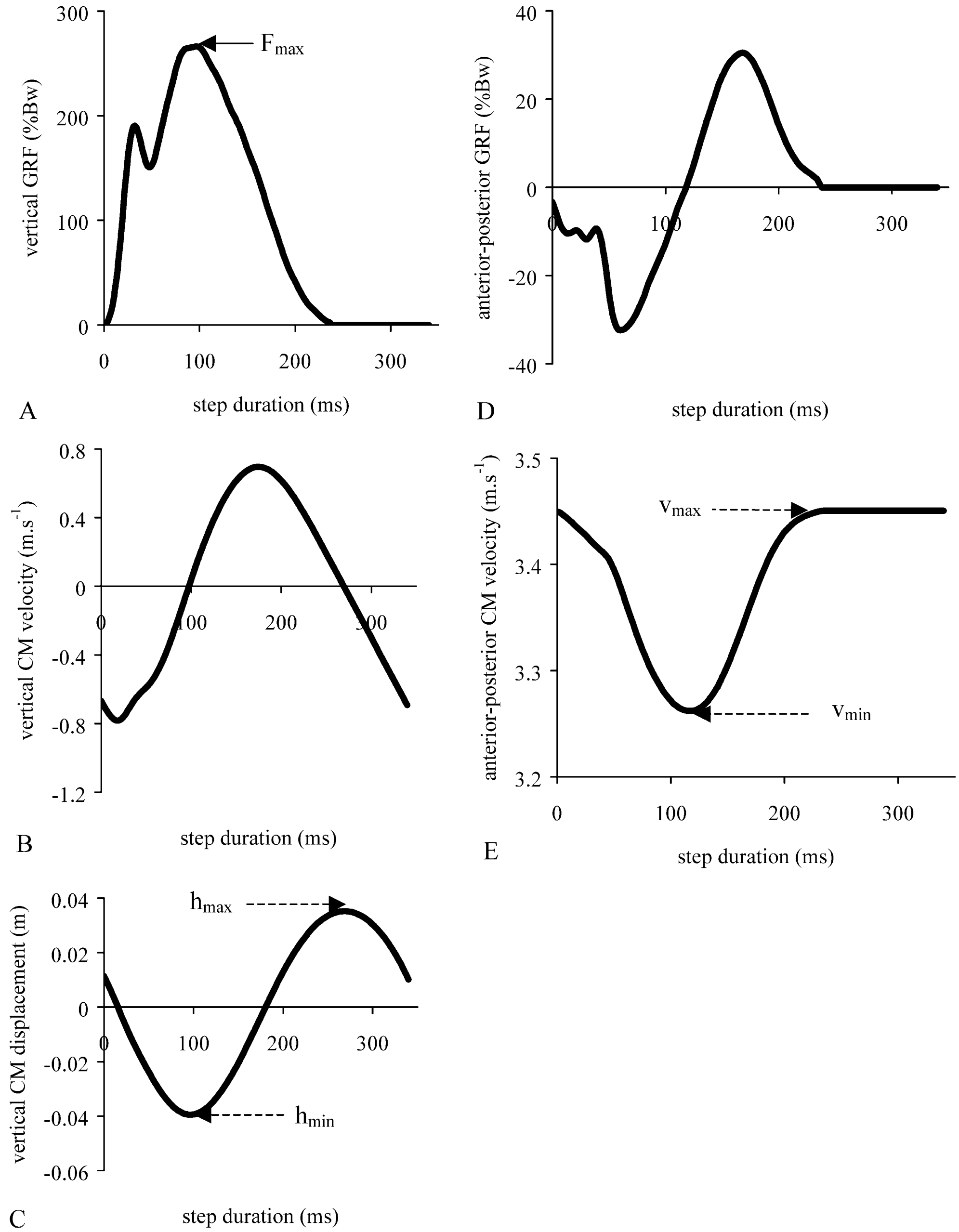

Fig. 1 Typical curves of vertical (**A**) and anterior-posterior (**D**) ground reaction forces (GRF) expressed as a percentage of the subject's body weight (%Bw), vertical (**B**) and anterior-posterior (**E**) speeds and vertical displacement (**C**) of the centre of mass (CM) during running at 12 km h^{-1}.F_{max} is the maximal vertical force, while $v_{max}$and v_{min} are the maximal and minimal anterior-posterior speeds respectively of the CM, while h_{min} and $h_{max}$are the minimal and maximal relative heights of the CM

ical work has been investigated and found to be < 6% for stiffness and ≤ 1% for the mechanical work parameters. CoV of the stride duration and of the vertical displacement have already been quantified by Belli et al. (1995) and have been found to be 1.8% and 7.5% respectively for speeds equivalent to those used in the

Table 1 Mean and standard deviation (SD) of the stride frequency, musculo-tendinous stiffness, kinetic (W_{kin}), potential (W_{pot}) and external (W_{ext}) works of the whole group under the different running conditions

Speed (km h^{-1})	Stride frequency (Hz)	Work (J kg^{-1} s^{-1})			Stiffness (kN m^{-1})
		W_{kin}	W_{pot}	W_{ext}	
12	1.39 (0.07)^{a,b,c}	1.88 (0.16)^{a,b,c}	2.42 (0.18)	4.30 (0.27)^{a,b,c}	15.0 (1.7)^{a,b,c}
14	1.43 (0.07)^{c}	2.53 (0.19)^{b,c}	2.43 (0.15)	4.95 (0.25)^{b,c}	14.1 (1.3)^{b,c}
16	1.46 (0.06)	3.15 (0.20)^{c}	2.46 (0.14)	5.61 (0.22)^{c}	12.3 (3.7)^{c}
18	1.49 (0.06)	3.87 (0.22)	2.44 (0.14)	6.31 (0.19)	11.8 (3.6)

[a]Significant difference ($P < 0.001$) at a speed of 14 km h^{-1}
[b]Significant difference ($P < 0.001$) at a speed of 16 km h^{-1}
[c]Significant difference ($P < 0.001$) at a speed of 18 km h^{-1}

Table 2 Inter-stride coefficient of variation [mean and (SD)] of the stride frequency, stiffness, W_{kin}, W_{pot} and W_{ext} under the different running conditions and for the whole group

Speed (km h^{-1})	Stride frequency (Hz)	Work (J $kg^{-1}s^{-1}$)			Stiffness (kN m^{-1})
		W_{kin}	W_{pot}	W_{ext}	
12	0.8 (0.3)	0.7 (0.7)	0.9 (0.3)	0.8 (0.4)[a]	5.1 (0.8)
14	0.9 (0.2)	0.4 (0.3)	0.9 (0.2)	0.7 (0.2)	4.9 (1.1)
16	0.9 (0.3)	0.6 (0.6)	1.0 (0.3)	0.7 (0.3)	4.9 (1.3)
18	1.0 (0.2)	0.3 (0.3)	1.0 (0.3)	0.5 (0.3)	5.1 (1.3)

[a]Significant difference ($P < 0.001$) at a speed of 18 km h^{-1}

present study. Here, the stride frequency did not vary by more than 1%. The subjects were highly trained endurance runners. As they were running at their self-chosen stride frequency, it is possible to speculate that they were running at a more comfortable speed since their CoV remained low compared to the subjects in the study of Belli et al.

A recent study from Masani et al. (2002) calculated the CoV of the GRF peaks in the vertical and anterior-posterior directions during walking. They reported values ranging from 2% to 15%, greater than those reported here for running. In the walking experiment, there was an influence of the speed on the CoV, which was not observed here. As the walking speed speeds ranged from 3 to 8 km h^{-1}(the fastest speed being 266% of the slowest), it could be hypothesised that the speed range used in the present study was not large enough to demonstrate any relationship between CoV and speed.

The main objective of this experiment was to compute the mechanical external work and musculo-tendinous stiffness during running on a treadmill ergometer. This method gave consistent results when compared to the literature. We suggest that this method could be extensively used to further investigate the modification and the evolution of mechanical parameters of running, with special reference to mechanical work and musculo-tendinous stiffness, for different running conditions.

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