# Energy Cost and Stride Pattern Variability of Elite Runners on the Treadmill

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## INTRODUCTION

Preliminary observations on individual freely chosen stride patterns during running at various velocities demonstrated discrepancies from those reported in the literature. This phenomenon was further investigated in relation to energy cost in 9 elite runners ($\overline{X} \pm s$, age: $27 \pm 4.5$ yr, height: $174.9 \pm 2.5$ cm, weight: $65.9 \pm 6.3$ kg and $\dot{V}O_{2max}$: $67.4 \pm 3.7$ ml $kg^{-1}$ $min^{-1}$). All runners had previous treadmill experience and performed a maximal multistage test. Initial treadmill speed of 9 km/h was increased by 1 km/h every 2 min. Measurements of stride frequency (accelerometer) and $\dot{V}O_2$ (Douglas bag method) started at 11 km/h.

As with $\dot{V}O_2$, the average values of stride length and stride frequency increase linearly with running speed, yielding high correlations in all cases ($r > 0.99$). The freely chosen stride pattern of individual runners however, was not always consistent with the average pattern. Discrepancies were more pronounced at low speeds, although they also occurred at high speeds associated with exhaustion.

This study demonstrates that not only the freely chosen stride pattern is well related to the energy demands, but also that the individual variations in stride length and stride frequency, as a function of running speed, counterbalance each other without affecting the linearity of the energy cost of running.

Although stride pattern is a significant aspect of running, metabolic data throughout various running speeds are inadequate. The two components of stride pattern, stride frequency (SF) and stride length (SL) when freely chosen, increase proportionally with running velocity (Williams, 1985). It is also well known that the energy cost of running increases linearly with the speed of running. Nevertheless, studies simultaneously presenting the relationship of $\dot{V}O_2$ and stride pattern throughout various running speeds are conducted at speeds lower than the competition range for distance runners.

From a biomechanical point of view, SF and SL have been thoroughly investigated. Studies on the changes of stride pattern with training (Nelson and Gregor, 1976; Girardin and Roy, 1984), fatigue (Buckalew et al., 1985; Cavanagh et al., 1985), and comparison of SL between elite and average (Hoshikawa, 1973) as well as good runners (Cavanagh et al., 1977) have been reported.

From a physiologic point of view however, the inadequately studied metabolic consequences have been mainly focused on running economy. Research on the energy cost during overstriding and understriding have been conducted (Hogberg, 1952; Cavanagh and Williams, 1982; Morgan and Martin, 1986). In general, it was demonstrated that the naturally selected SL was optimal or very close to optimal. Nevertheless, this constructive combination of physiological and biomechanical data is limited to few selected running speeds, to small number of subjects and to absence of statistical analysis.

Thus, the purpose of this study is to investigate the relationship between energy cost and stride pattern (frequency and length) during progressively increasing running speeds in elite distance runners. Particular attention is also given to the inter-individual variability of SL and SF as a function of speed.

**METHODS**

Nine elite male distance runners, scoring above 770 points on the Gardner and Purdy (1970) scale, participated in this study. Each athlete was informed of the stresses and risks associated with the experimental protocol before giving his written consent. The subjects were $27 \pm 4.5$ ($\overline{X} \pm SD$) years of age, weighed $65.9 \pm 6.3$ kg, and measured $174.9 \pm 2.5$ cm in height. They had treadmill experience, and they performed a maximal multistage running test on a horizontal treadmill. Initial speed of 9 km/h

was increased by 1 km/h every 2 min. Measurements of stride frequency and oxygen consumption started at the speed of 11 km/h. The first two running stages were included in the adaptational and warm-up period.

Using a waist-attached accelerometer connected to a recorder, the stride frequency was determined from the registered contact points of the same foot. The frequency of stride per minute was computed from a recording chart (50 mm/s) for a 30 s period during the second minute of each incremental stage. Stride length (SL), expressed in meters, was defined as the distance of a complete cycle between two consecutive contacts of the same foot, and was calculated from SF and treadmill speed, which was calibrated prior to testing.

Oxygen uptake was measured during the last minute of each 2 min stage. Expired air was collected in neoprene bags through a Collins low resistance valve, and its volume was measured by a Tissot spirometer. Expired $O_2$ and $CO_2$ fractions were determined from a constant sample using the Beckman E-2 and Beckman LB-2 gas analyzers.

## RESULTS

Table 1 presents $\dot{V}O_2$, SF and SL values ($\overline{X} \pm$ SD and range) at each running speed. The trend of the linearly increasing SF and SL as a

## TABLE 1

Mean, standard deviation and range values of energy cost, stride frequency and stride length throughout the performed running speeds

| Speed km/h | VO₂, ml/kg min | | Stride frequency, strides/min | | Stride length, m | | Subjects N |
|---|---|---|---|---|---|---|---|
| | Mean ± SD | Range | Mean ± SD | Range | Mean ± SD | Range | |
| 11 | 31.81±5.28 | 22.31−36.25 | 87.5±4.4 | 80.7− 97.1 | 2.09±0.10 | 1.89−2.27 | 9 |
| 12 | 34.17±4.81 | 25.82−39.64 | 88.1±4.6 | 80.9− 97.9 | 2.27±0.12 | 2.04−2.68 | 9 |
| 13 | 37.71±4.21 | 29.70−42.37 | 88.9±4.9 | 81.2− 98.8 | 2.46±0.15 | 2.19−2.47 | 9 |
| 14 | 40.77±4.37 | 33.42−46.15 | 89.4±5.0 | 82.4− 99.7 | 2.61±0.14 | 2.34−2.83 | 9 |
| 15 | 44.07±3.98 | 37.50−50.05 | 90.2±5.2 | 83.1−100.9 | 2.77±0.15 | 2.48−3.01 | 9 |
| 16 | 48.03±3.56 | 42.03−53.18 | 91.1±5.2 | 84.7−101.9 | 2.93±0.16 | 2.62−3.14 | 9 |
| 17 | 51.95±3.66 | 46.37−58.76 | 92.2±5.5 | 85.7−103.0 | 3.08±0.17 | 2.75−3.30 | 9 |
| 18 | 56.40±3.81 | 49.99−63.19 | 93.5±5.5 | 86.6−104.4 | 3.21±0.18 | 2.88−3.46 | 9 |
| 19 | 60.01±3.34 | 54.34−65.98 | 94.5±5.9 | 87.7−105.3 | 3.36±0.20 | 3.01−3.61 | 9 |
| 20 | 65.32±2.85 | 61.29−69.40 | 95.6±6.3 | 89.9−106.5 | 3.50±0.22 | 3.13−3.70 | 9 |
| 21 | 68.98±3.35 | 65.73−72.35 | 98.9±7.8 | 91.9−107.2 | 3.54±0.27 | 3.26−3.77 | 4 |
| 22 | 68.69±0.54 | 68.31−69.07 | 100.9±9.5 | 94.2−107.7 | 3.64±0.35 | 3.40−3.89 | 2 |

function of speed as well as the large inter-individual variability of SF and SL is better observed in Figures 1 and 2. Similar observations could be made when the energy cost is plotted against running speed (Figure 3). Basically, the same trend occurs in SL and SF curves when running speed is exchanged with the energy cost of running (Figure 4).
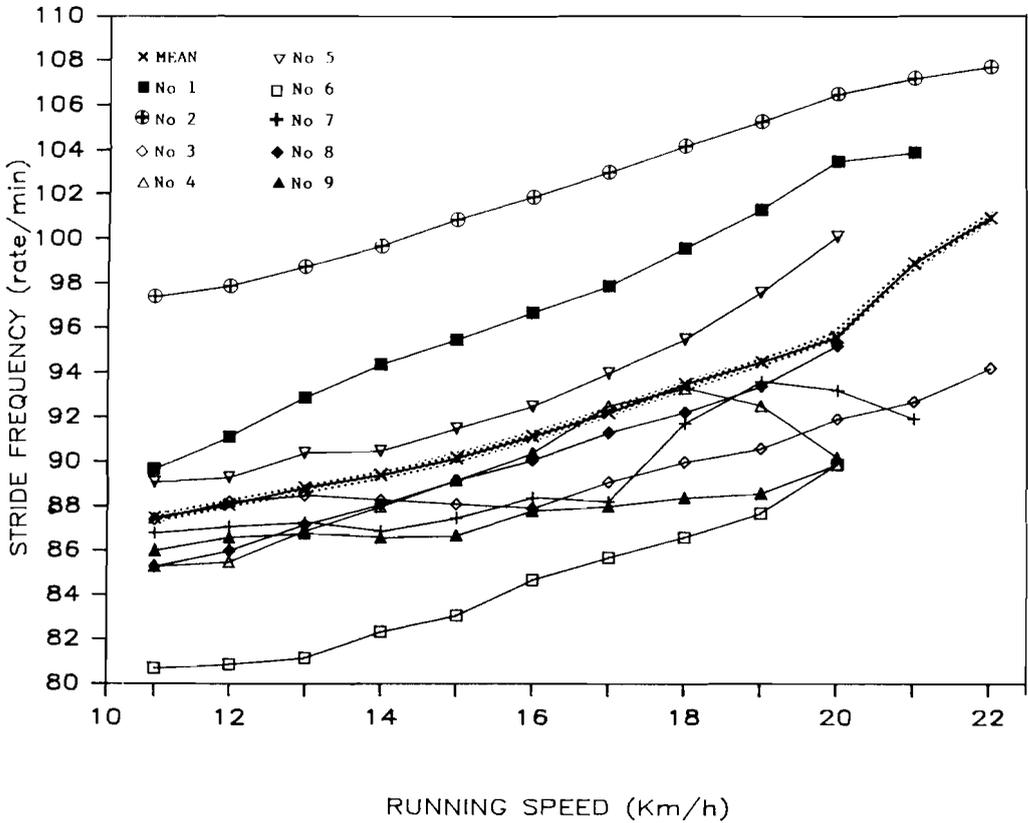


Fig. 1 Individual and average manual plotting of stride length as a function of running speed.
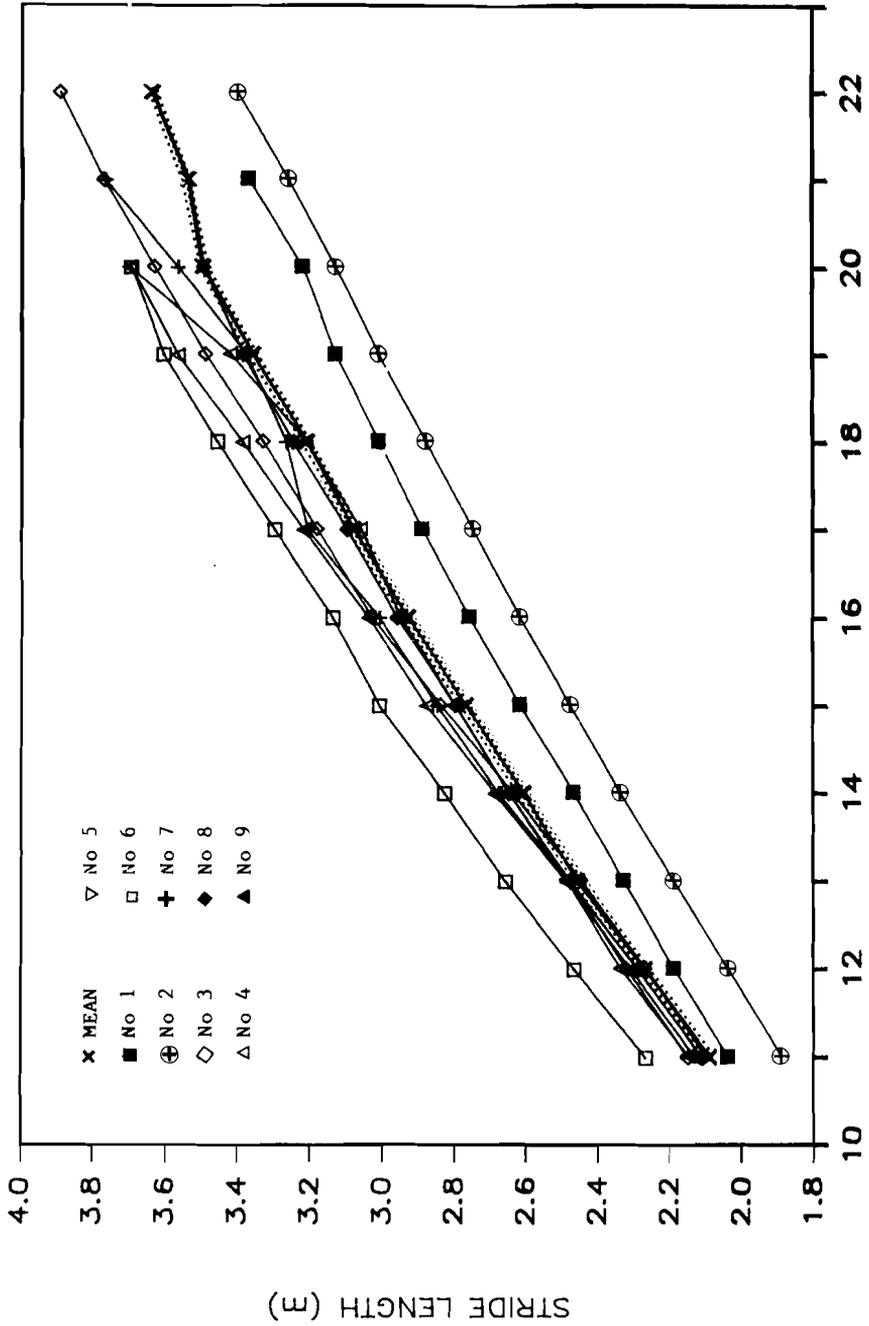
426



Fig. 2 Individual and average manual plotting of stride frequency as a function of running speed.
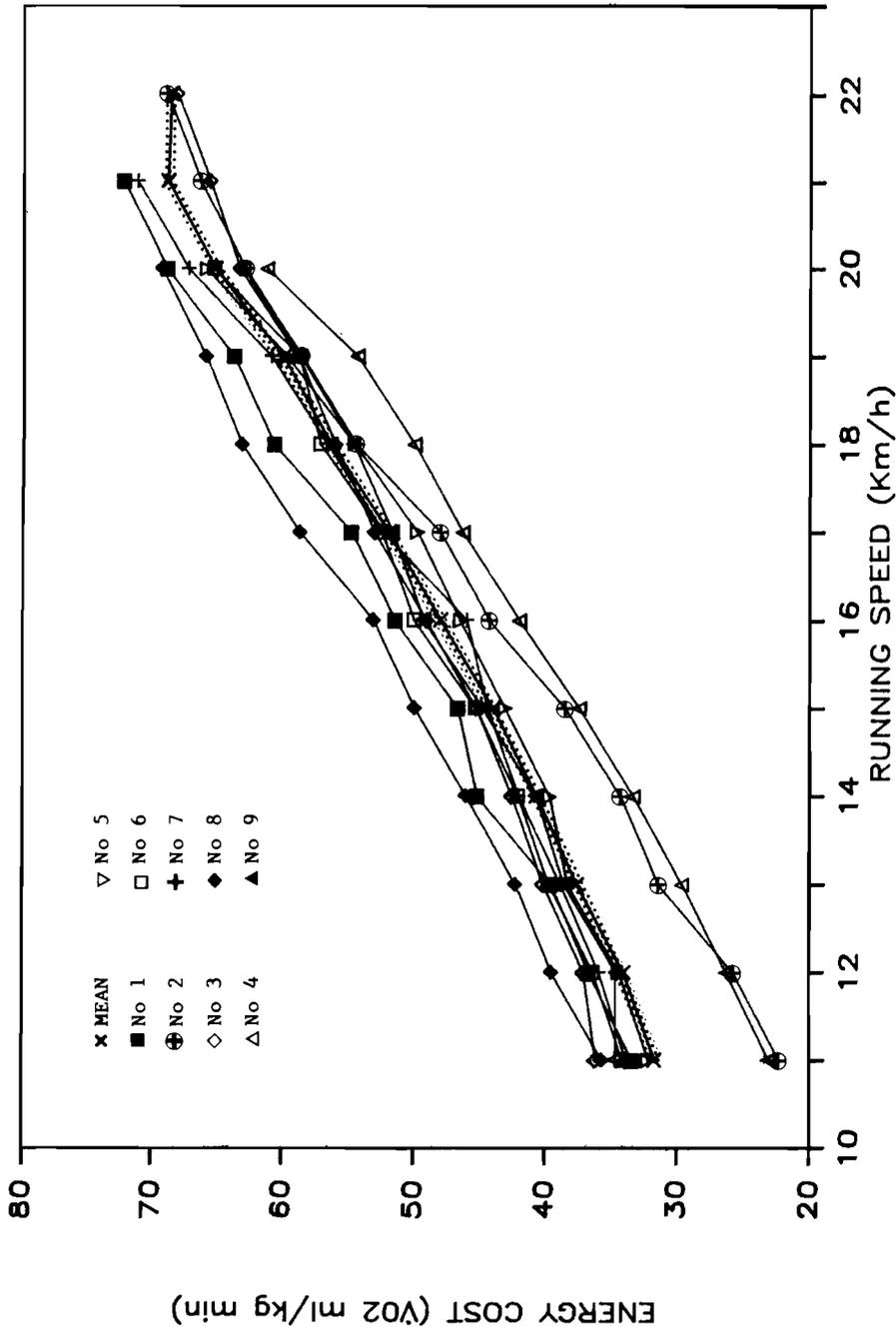
Fig. 3 Individual and average manual plotting of energy cost as a function of running speed.
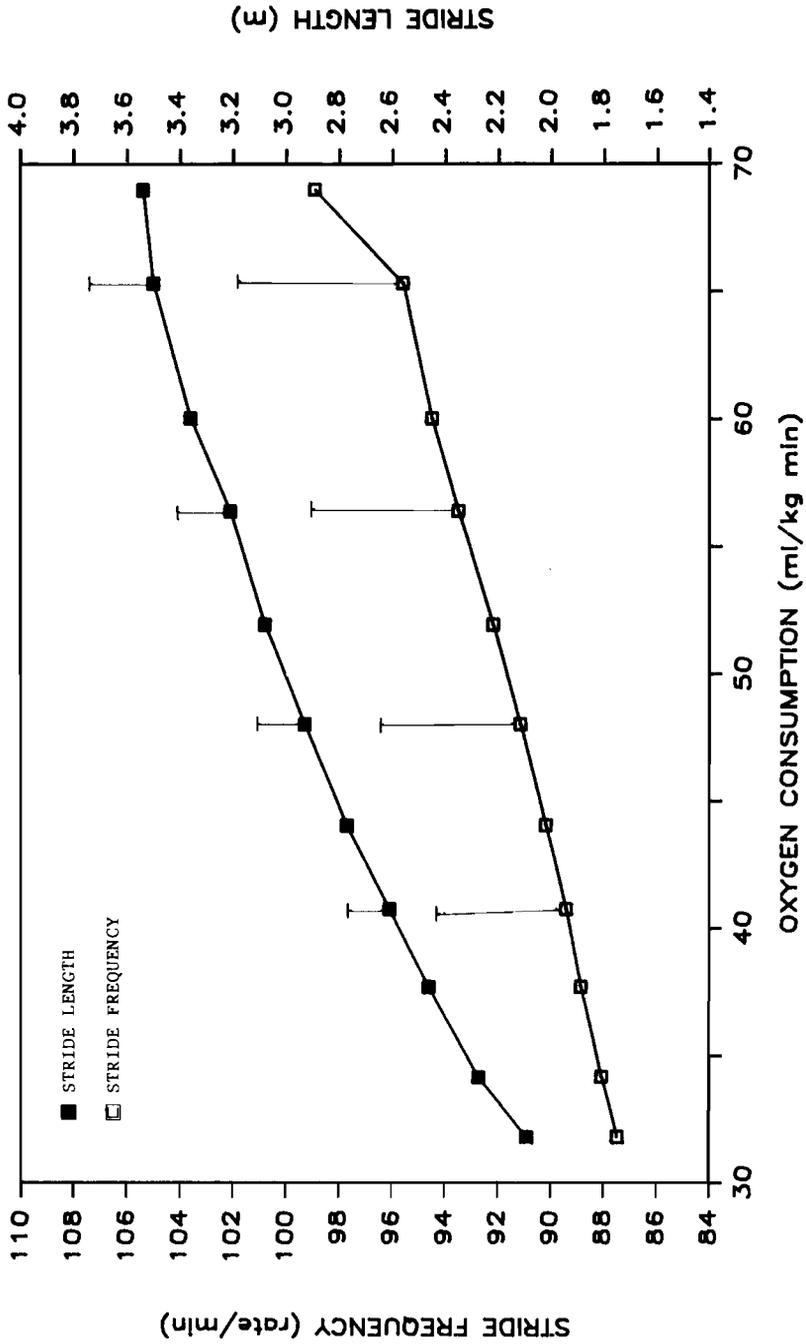
427

Fig. 4 Average values of stride length and stride frequency plotted as a function of energy cost of running.

These manually plotted illustrations are mathematically confirmed with regression analyses (Table 2). Correlations obtained with mean values through the entire range of 11 to 20 km/h were very high ($r > 0.99$). On the other hand, correlations with the same variables, combining data of all subjects, were lower particularly in the case of SF. Standard error of estimate was also higher in the regressions computed with all the data (Table 2). This demonstrates the high inter-individual variability of these variables.

## TABLE 2

Correlation coefficients, regression equations and standard error of estimates between running speed, energy cost ($VO_2$, ml/kg min), stride length (SL, m) and stride frequency (SF, strides/min) calculated from all data (n=90) and the mean values at each speed (n=10) up to 20 km/h

| X | Y | DATA BASE, | n | r | EQUATIONS Y=b+ax | SEE, % Y |
|---|---|---|---|---|---|---|
| $VO_2$ | SL | ALL DATA | 90 | 0.863 | y= 1.1765+0.0350x | 8.53 |
| | | MEAN VALUES | 10 | 0.992 | y= 0.8824+0.0414x | 2.23 |
| $VO_2$ | SF | ALL DATA | 90 | 0.374 | y= 82.3758+0.1856x | 5.80 |
| | | MEAN VALUES | 10 | 0.998 | y= 79.5389+0.2458x | 0.17 |
| SPEED | $VO_2$ | ALL DATA | 90 | 0.934 | y=−10.422 +3.6983x | 8.72 |
| | | MEAN VALUES | 10 | 0.997 | y=−10.600 +3.7177x | 2.07 |
| SPEED | SL | ALL DATA | 90 | 0.945 | y= 0.4224+0.1553x | 5.50 |
| | | MEAN VALUES | 10 | 0.999 | y= 0.4194+0.1554x | 0.85 |
| SPEED | SF | ALL DATA | 90 | 0.464 | = 76.974 +0.9115x | 5.55 |
| | | MEAN VALUES | 10 | 0.992 | y= 76.971 +0.9114x | 0.39 |

Coefficients of determination ($r^2$) indicate that speed explains 87.6% of $\dot{V}O_2$ variance whereas SL and SF, respectively explain 79.6 and 13.6% of $\dot{V}O_2$ variance. These values are obtained with first degree correlations. Because SL is highly ($r = 0.936$) but SF poorly ($r = 0.464$) correlated with speed, multiple regression and partial correlations were performed. When data were analyzed for all subjects at all speeds, only speed was found to affect significantly the $\dot{V}O_2$. The partial correlations of SF and SL were only $-0.21$ and $+0.15$.

Running $\dot{V}O_{2max}$ ($X_1$, ml/kg min) running economy ($\dot{V}O_2$ at 16 km/h, $X_2$, ml/kg min), SF at 16 km/h ($X_3$, strides/min) and SL at 16 km/h ($X_4$, m/stride) are often seen as performance indices. Their ability to predict the maximal running speed during the multistage test (Y, km/h) is as follows:

$$Y = 12.74 + 0.158X_1 - 0.097X_2 + 0.021X_3 \qquad (1)$$

with a multiple correlation of 0.70, a SEE of 3.8% of Y (n = 9). SL does not enter the regression. The Beta coeffcients are 0.67, $-0.40$ and 0.13 for $X_1$, $X_2$ and $X_4$, whereas first degree correlations are 0.56, $-0.15$, 0.49, respectively. First degree correlation between $X_4$ and Y is $-0.48$.

## DISCUSSION

The results of the present study (combined observations on all the subjects, n = 90) demonstrate that the relationship found between energy cost and speed of running (r = 0.934) is similar with the relationship of freely chosen SL and running speed (r = 0.945). This relationship is however much lower (r = 0.464) for the SF variable. Similar trends appear when SL and SF are correlated with $\dot{V}O_2$ (Table 2). Roy (1982) also reported a higher correlation between SL and running speed (r = 0.88) as compared to SF (r = 0.52). As it appears from Table 2 however, correlation coefficients with mean values are always extremely high (r > 0.99). As seen with Figures 1 to 3, this trend is also valid for individual curves (r $\geqq$ 0.96 except subjects Nos 4 and 7) indicating a low intra-individual variability that is contrasted with the high inter-individual variability. Use of mean values obviously hides the high inter-individual variability suggesting caution in individual application of regressions calculated by mean values. Furthermore, in the cases of subjects 4 and 7 the stride frequency is decreasing near maximal speeds contrary to the average patterns (Figure 1). Of course, intra-individual variations on these runners affect the linear regression analyses and yield lower correlations (No 4: r = 0.85 and No 7: r = 0.90).

In general, the shape of average SF and SL curves are similar to that in previous reports in the literature (Luhtanen and Komi, 1978). The individual deviation from the average values, however, points out the need for an individualized approach in elite runners. For every runner, there is an optimum SL and SF (i.e. lower $\dot{V}O_2$) at each running speed (Hogberg, 1952). Fatigue can affect the optimal SL, however. At the end of a marathon race for instance, Buckalew et al. (1985) found that the runners decreased their speed as a result of SL decrease while SF stayed the same. Moreover, their best performers overcame this effect somewhat more than their poorer performers. Thus, even though each individual has his/her own optimal SL and SF, information on SF and SL with fatigue could be useful for selecting the best runners. In this regard, the present study demonstrated that the shorter event runners (v.g. No 6,

5000 m) have lower SF and higher SL than the longer event runners (v.g. No 1, 42,2 km and No 2, 20 km) when running at the same speed, (Figures 1 and 2).

For a very short event such as the maximal multistage test performed in this study, it was found that the maximal speed was negatively related to $\dot{V}O_2$ and SL at 16 km/h, but positively to $\dot{V}O_{2max}$ and SF at 16 km/h (equation 1). $\dot{V}O_{2max}$ and $\dot{V}O_2$ at 16 km/h were also the most important factors when predicting the maximal speed. Thus, for a particular event, a short one in this instance, the lower the SL or the higher the SF, the better the performance. To confirm these results however, runners over various distances, and measurements for each specific distance are required. Nevertheless, as suggested by Clarke et al. (1985), higher SF would reduce joint forces and impact loading, and would also be beneficial to the athlete's career.

In 1944, Boje was the first who suggested that the speed was merely increased with an increase in SL while SF only slightly increased in speeds ranging from 10 to 18 km/h. Similar results were also reported on one subject up to 16 km/h by Knuttgen in 1961. Our study basically agrees with these previous studies (Figure 4). Considering the investigated speeds (11 to 22 km/h) however, over 20 km/h the average relationship of SF and SL appears to be inversed. This is also confirmed by other studies over 18 km/h (Hogberg, 1952 and Luhtanen and Komi, 1978). Thus, the evaluation of SL and SF in athletes should take into consideration their average running speed in competition or their distance specialty.

With regard to the absolute values of SL and SF at any particular speed, the present study is in agreement with data reported by Boje (1944), Hogberg (1952) and Knuttgen (1961) but disaccordant with data reported by Luhtanen and Komi (1978) without any obvious explanation. Apart from our study, there is only one other (Van der Walt and Wyndham, 1973) which used multiple regression analysis to investigate $\dot{V}O_2$ cost and stride pattern as a function of speed. For that study, six untrained males with wide range in body mass (62.8 to 102 kg), ran at low speeds (8-13 km/h) on the treadmill. It was found that body mass and speed alone can predict the $\dot{V}O_2$ and that SL and leg length were negligible (2%) predictors. Body mass was not significant in our homogeneous group of elite runners. Otherwise, our study conducted at higher speeds yielded similar results with speed alone being a significant predictor of energy cost.

In conclusion, the present study although confirming previous studies on a wider range of running speeds, strongly indicates that large

inter-individual variability prevents excessive application of the average trends to any individual and that evaluation of running characteristics such as running economy, stride length, and stride frequency should be evaluated within an individual perspective.

## REFERENCES

Boje, O., Energy production, pulmonary ventilation, and length of steps in well-trained runners working on a treadmill. *Acta Physiologica Scandinavica*, 7: 362-375, 1944.

Buckalew, D. P., Barlow, D. A., Fischer, J. W. and Richards, J. G., Biomechanical profile of elite women marathoners. *International Journal of Sport Biomechanics*, 1: 330-347, 1985.

Cavanagh, P. R., Andrew, G. C., Kram, R., Rodgers, M. M., Sanderson, D. J. and Henning, G. W., An approach to biomechanical profiling of elite distance runners. *International Journal of Sport Biomechanics*, 1: 36-62, 1985.

Cavanagh, P. R., Pollock, M. L. and Landa, J. (1977), A biomechanical comparison of elite and good distance runners. In: P. Milvy (ed.). *The Marathon: Physiological, Medical, Epidemiological and Psychological Studies*, (pp. 328-345), New York: New York Academy of Sciences, 1977.

Cavanagh, P. R. and Williams, K. R., The effect of stride length variation on oxygen uptake during distance running. *Medicine Science in Sports and Exercise*, 14(1): 30-35, 1982.

Clarke, T. E., Cooper, L. B., Hamill, C. L. and Clark, D. E., The effect of varied stride rate upon shank deceleration in running. *Journal of Sports Sciences*, 3: 41-49, 1985.

Elliott, B. C. and Roberts, A. D., A biomechanical evaluation of the role of fatigue in middle-distance running. *Canadian Journal of Applied Sport Sciences* 5(4): 203-207, 1980.

Girardin, Y. and Roy, G. B., Effects of nondirective type of training program on the running patterns of male sedentary subjects. In: R. C. Nelson and C. A. Morehouse (eds.), *Biomechanics IV*, (pp. 119-125), Baltimore: University Park Press, 1984.

Hogberg, P., How do stride length and stride frequency influence the energy-output during running? *Arbeitsphysiology*, 14: 437-441, 1952.

Hoshikawa, T., Matsui, H. and Miyashita, M., Analysis of running pattern in relation to speed. In: S. Cerquiglini, A. Venerando and J. Wartenweiler (eds.), *Medicine and Sport, vol. 8: Biomechanics III*, (pp. 342-348), Baltimore: University Park Press, 1973.

Knuttgen, H. G., Oxygen uptake and pulse rate while runing with undetermined and determined stride lengths at different speeds. *Acta Physiologica Scandinavica*, 52: 366-371, 1961.

Luhtanen, P. and Komi, P. V., Mechanical factors influencing running speed. In: E. Asmussen and K. Jorgensen (eds.), *International Series on Biomechanics, Vol. 2B: Biomechanics VI-B*, (pp. 23-29), Baltimore: University Park Press, 1978.

Morgan, D. W. and Martin, M. E., Effects of stride length alteration on racewalking economy. *Canadian Journal of Applied Sport Sciences, 11(4):* 211-217, 1986.

Nelson, R. C. and Gregor, R. J., Biomechanics of distance running: A longitudinal study. *Research Quarterly, 47(3):* 417-428, 1976.

Gardner, J. B. and Purdy, G. J., *Computerized running training programs.* Tafnews Press, Los Altos, Califormia, 1970.

Roy, B., Caractéristiques biomécaniques de la course d'endurance. *Canadian Journal of Applied Sport Sciences, 7(2),* 104-115, 1982.

Van Der Walt, W. H. and Wyndham, C. H., An equation for prediction of energy expenditure of walking and running. *Journal of Applied Physiology, 34(5):* 559-563, 1973.

Williams, K. R., Biomechanics of running. In: R. T. Tergung (ed.), *Exercise Sports Sciences Reviews, Vol. 13*, (pp. 389-441), American College of Sports Medicine Series, New York: MacMillan Publishing Company, 1985.

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