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The effect of stride length variation on oxygen uptake during distance running

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ABSTRACT

CAVANAGH, PETER R. and KEITH R. WILLIAMS. The effect of stride length variation on oxygen uptake during distance running. *Med. Sci. Sports Exercise.* Vol. 14, No. 1, pp. 30-35, 1982. Ten recreational runners (mean $\dot{V}O_{2max}$ 64.7 $ml \cdot kg^{-1} \cdot min^{-1}$) underwent a 5-d acclimation period to treadmill running at a 7 $min \cdot mile^{-1}$ pace (3.83 $m \cdot s^{-1}$) for 30 min each day. During these runs their freely chosen stride lengths were determined and expressed as a percentage of leg length (%LL). On two subsequent testing days stride length was systematically varied over a range of ± 20% LL about the freely chosen value. O_2 uptake was determined by the Douglas Bag method. All subjects exhibited a stride length at which O_2 uptake was minimized, although the individual profiles varied considerably. The mean increases in $\dot{V}O_2$ were 2.6 and 3.4 $ml \cdot kg^{-1} \cdot min^{-1}$ at the short- and long-stride length extremes, respectively. During unrestricted running deviations from optimal stride length caused a mean increase in $\dot{V}O_2$ of 0.2 $ml \cdot kg^{-1} \cdot min^{-1}$. The relatively efficient running patterns used by the subjects during unrestricted running indicate either an adaption to the chosen stride length through training or a successful process of energy optimization.

BIOMECHANICS OF RUNNING, ENERGY OPTIMIZATION, RUNNING EFFICIENCY, TREADMILL ACCLIMATION, STRIDE LENGTH

During steady-speed running there is an infinite number of combinations of stride length (SL) and stride frequency (SF) which a runner may adopt. The process by which a runner selects a particular combination would appear to be both self-determined and subconscious since most coaches prefer to leave this aspect of running style to the athlete (4) who in turn does not usually systematically experiment with various stride lengths.

The variation of stride length and stride frequency with running speed has been well-documented (3). However, there is evidence that the chosen combination of stride length and stride frequency at a fixed speed may change with time. Nelson and Gregor (9) found a group of distance runners, during the 4 yr of their varsity careers, shortened their stride at a given speed by an average of 7 cm. The simple process of shortening or lengthening the stride has an important effect on all of the active musculature. Each muscle is forced to work on a slightly different region of its force-velocity curve and consequently changes in efficiency can be anticipated (13).

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Högberg (7) reported, from experiments on a single subject, that at every running speed an optimal stride length exists at which oxygen uptake is minimized. From observations at stride lengths approximately ± 17% of leg length from the freely chosen stride length, he found increases in oxygen uptake of up to 6% at the shorter strides and 12% when the subject was forced to take longer strides. Högberg stated that the freely chosen stride length was the most economical one of those tested as measured by oxygen uptake. An examination of the raw data presented by Högberg suggests the possibility that a least-squares-fit may shift the minimum to a stride length which would be between two of those used in the experiment. Also, since the data are from a single subject it is not possible to generalize the results to a larger population. It would be of interest to know, for example, if overstriding by a certain percentage of leg length is always more costly than the same amount of understriding. In addition, it needs to be determined whether or not the optimal condition for all runners corresponds with their freely chosen stride length.

Knuttgen (8) presented results from one subject running at a range of velocities while stride length was held constant to the length freely chosen by the subject at the slowest speed. As running speed increased, a progressively greater increment in oxygen uptake was required which was attributed to increasingly larger deviations from optimal stride length. These results are in basic agreement with those of Högberg such that slight deviations from optimal conditions produce little or no variations in oxygen uptake; but, that large deviations become increasingly costly.

The literature to date provide no information concerning the magnitude of typical deviations from optimal conditions of stride length and oxygen uptake found in trained runners. In developing an equation for the prediction of energy expenditure during running using six untrained subjects, Van der Walt and Wyndham (12) found neither stride length nor leg length (LL) to be an important predictor of oxygen consumption. Stride length accounted for only 0.7% of the total variance and leg length only 1.3%. The exact influence of stride length may have been confounded somewhat since absolute SL measurements were used rather than values relative to leg length, despite a wide variation in the body size of the subjects. It may be that relative measures would be more closely related to oxygen uptake variations since correlations between leg length and stride length are generally high, at least for fast running speeds (3).

The present experiment was basically a replication of Högberg's original study using a larger number of subjects and employing curve-fitting techniques to predict the stride length at which oxygen uptake is minimized. In this paper submaximal oxygen consumption was used as a measure of physiological efficiency. Though other criteria could alternatively have been used, this measure has been used by others as an indicator of either efficiency or running economy (2,6,10) and seemed best suited to the data presented here. The lower the oxygen uptake, the more physiologically efficient the runner was assumed to be.

METHODS

Subjects

Ten male runners, who averaged 40-110 miles of distance running per week, were used as subjects in this experiment. Informed consent of the subjects was obtained in accordance with the policy statement of the American College of Sports Medicine. Table 1 lists the physical characteristics of each subject and shows that they were a fit group with a mean $\dot{V}O_{2max}$ of 64.7 $ml \cdot kg^{-1} \cdot min^{-1}$.

Measurement of Stride Length

To measure the stride length during treadmill running, advantage was taken of the fact that the belt speed changes slightly during each foot contact. This fluctuation can be readily seen on the speed indicator, and the changing voltage signal to this meter was amplified and recorded on a chart recorder.

The number of foot contacts with the treadmill in a 20-s period were determined from the chart recording to the nearest 0.1 of a stride. The stride time (ST), representing the average time between successive foot contacts, was then calculated. An estimate of mean treadmill velocity (V) was obtained for each trial by counting the number of complete belt revolutions in a 4-min period while subjects ran at the nominal speed of 3.83 $m \cdot s^{-1}$. Stride length, defined as the average distance between successive foot contacts, was then calculated using the relationship:

$$SL = V \times ST$$

For example, if 58.5 strides occurred during the 20-s observation period the mean stride time was 0.342 s. At a measured belt speed of 3.75 $m \cdot s^{-1}$, the mean stride length for this condition would be 1.28 m. Stride length was also expressed as a percentage of the subject's leg length, measured between the superior border of the greater trochanter and the floor during easy barefoot standing.

Oxygen Consumption

Oxygen consumption ($\dot{V}O_2$) was measured using the Douglas Bag technique. Thirty seconds prior to each gas collection subjects put on a nose clip and inserted a mouthpiece attached to a flexible air hose suspended in front of them in such a way as to minimize any interference with normal running patterns. During each collection period two 1-min samples of expired air were collected and subsequently analyzed for percent O_2 and CO_2 using a Beckman O_2 analyzer model OM 11 and a Lira infrared CO_2 analyzer model 300. Following gas collection the mouthpiece and noseclip were removed until the next collection period.

Acclimation Phase

In order to determine the freely chosen SL and to insure that subjects were acclimated to the treadmill, in terms of both oxygen consumption and SL, each individual underwent five half-hour training sessions over a 10-d period. The speed of running was 3.35 $m \cdot s^{-1}$ (8 $min \cdot mile^{-1}$) for the first 5 min and 3.83 $m \cdot s^{-1}$ (7 $min \cdot mile^{-1}$) for the remainder of the run. Expired air was collected during minutes 8-10, 18-20, and 28-30, and stride length measurements were made during minutes 9-10, 14-15, 19-20, 24-25, and 29-30.

TABLE 1. Physical characteristics, chosen and optimal $\dot{V}O_2$ and stride length data for all subjects.

Subject	Weight (kg)	Height (cm)	Leg length (cm)	$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	Chosen $\dot{V}O_2$* ($ml \cdot kg^{-1} \cdot min^{-1}$)	Chosen Stride length (cm)	Optimal $\dot{V}O_2$* ($ml \cdot kg^{-1} \cdot min^{-1}$)	Optimal Stride length* (cm)	| ΔStride length | ** (cm)
1	72.6	184.1	95.3	59.4	41.2	128.1	41.2	125.2	2.9
2	73.9	186.4	96.9	62.3	45.4	122.5	45.2	126.2	3.7
3	68.5	179.1	93.8	68.2	45.9	141.2	45.8	137.5	3.7
4	73.9	179.1	93.4	65.0	45.8	135.2	45.3	126.1	9.1
5	66.7	180.3	94.9	64.8	48.2	129.0	48.0	132.7	3.7
6	70.8	181.0	93.1	73.3	52.9	137.3	52.7	131.6	5.7
7	66.2	175.3	89.4	64.7	45.2	129.7	44.4	123.1	6.6
8	80.3	182.9	95.3	72.3	44.9	129.6	44.8	127.2	2.4
9	70.8	175.3	91.0	54.7	43.3	128.1	43.2	130.8	2.7
10	76.7	171.5	84.2	62.0	46.6	140.5	46.6	139.1	1.4
Mean	72.0	179.5	92.7	64.7	45.9	132.1	45.7	129.9	4.2
(SD)	(4.4)	(4.5)	(3.7)	(5.6)	(3.1)	(6.1)	(3.1)	(5.4)	(2.3)

*Derived from individual SL-$\dot{V}O_2$ regression equations for each subject.

** | ΔStride length | represents the absolute deviation from optimal stride length.

Both SL and $\dot{V}O_2$ from the training phase were examined with a 2-way ANOVAR (within and between days) with repeated measures. The oxygen uptake during the first of the three collection periods were found to be significantly different ($P<0.05$) from the subsequent values (means of 45.7, 46.7, and 46.9 $ml \cdot kg^{-1} \cdot min^{-1}$), indicating the importance of a warm-up period. There were no significant differences from oxygen uptake between days and none of the SL comparisons revealed significant differences. The freely chosen stride length was taken as the mean of the measured SL at the end of minutes 15, 20, and 25 on all of the five training days.

Experimental Phase

For each individual, seven stride lengths were determined at which oxygen uptake measurements were made. One of these was the freely chosen SL, and the remaining six values deviated by ± 6.7%, ± 13.4%, and ± 20% of leg length from the freely chosen SL. Since the velocity of the treadmill was precisely known, a necessary stride time to achieve the required SL could be determined. An electronic metronome was set to generate loud audible signals at intervals of the ST, which represented the time between successive foot contacts with the treadmill. Subjects found little difficulty in timing their footfalls with the metronome. Regardless of how closely they followed the metronome, an accurate estimate of actual stride length used during data collection was made by the method previously described.

The following protocol was used during the experimental phase. An 8-min warm-up was performed at the experimental speed of 3.83 $m \cdot s^{-1}$ (7 $min \cdot mile^{-1}$). Seven blocks of an 8-10 min rest period followed by a 6-min data collection period were then performed with the seven different stride lengths being presented in a random sequence. SL and oxygen uptake data were collected during minutes 4-6 of each of the seven conditions. The subjects returned to the laboratory within 4 d and the experiment was replicated using a different random sequence of the same stride lengths.

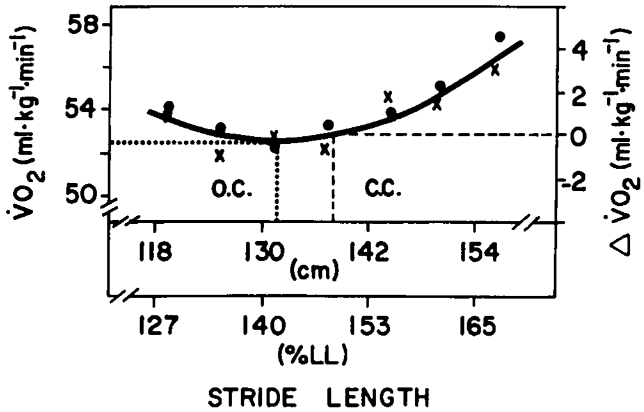

Figure 1—Results for a typical subject (subject 6) under all experimental conditions. The smooth curve is a quadratic least squares fit to the data points from both experimental days (x day 1, • day 2). The small difference between $\dot{V}O_2$ at the chosen condition (C.C.) and optimal condition (O.C.) indicates that the subject is running with an SL which is close to being the most efficient at this speed.

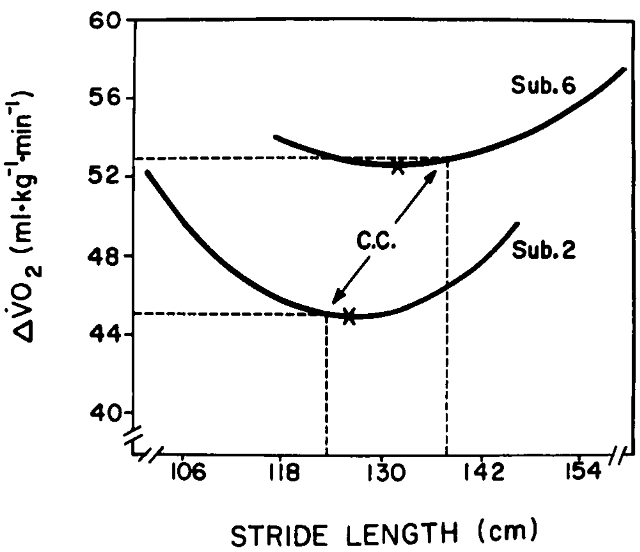

Figure 2—Best-fit curves for two subjects showing different responses to the experimental conditions. The cross on each curve represents the optimal conditions while the dashed lines show the chosen condition. Subject 2 shows a smaller O_2 uptake, and shorter stride lengths than subject 6. It should be noted that subject 2 has a longer leg length than subject 6 (see Table 1).

RESULTS

A typical set of data for one subject at all stride lengths is shown in Figure 1 where the individual data points from both experimental days are shown. The regression line shown in the figure is a best-fit quadratic curve where the minimum represents the most efficient stride length designated the optimal condition (OC). The oxygen uptake at the chosen condition (CC) was determined by substitution of the chosen stride length into the polynomial equation.

Quadratic curves gave the best least-squares-fit to the data from eight subjects, while the remaining two were better fitted by third degree equations.

There was a considerable range of oxygen uptakes, chosen stride lengths, and responses to the experimental treatment within the group of 10 subjects. This is emphasized by the results of two subjects shown in Figure 2. At their optimal stride lengths the subjects shown in this figure have an oxygen uptake which differed by 7.5 $ml \cdot kg^{-1} \cdot min^{-1}$ and stride lengths which differed by 4.5 cm with the shorter strides being taken by the subject with the greater leg length. It is also apparent from the figure that one subject showed greater increases in oxygen uptake at the shorter stride lengths, while the other exhibited the greatest increase at long stride lengths. The values for stride length and oxygen uptake for all subjects at chosen and optimal conditions are given in Table 1. All stride

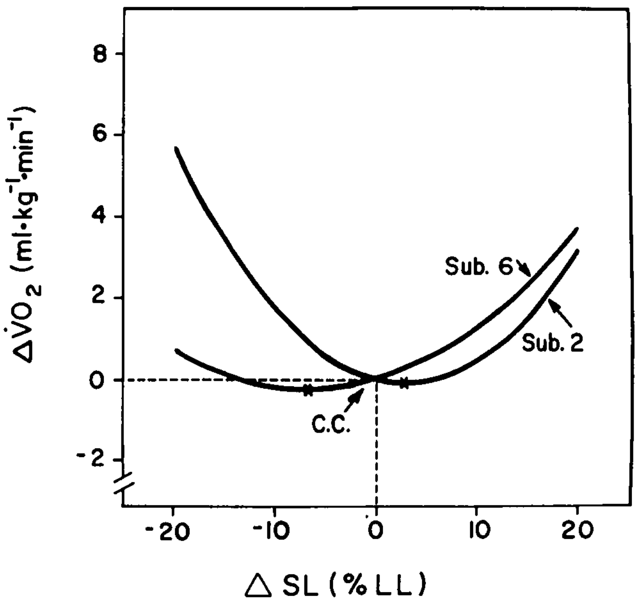

Figure 3—The same data shown in Figure 2, plotted in terms of change of oxygen uptake and stride length from chosen conditions (C.C.). Both curves therefore, pass through the origin. Crosses represent the optimal conditions. See text for further discussion.

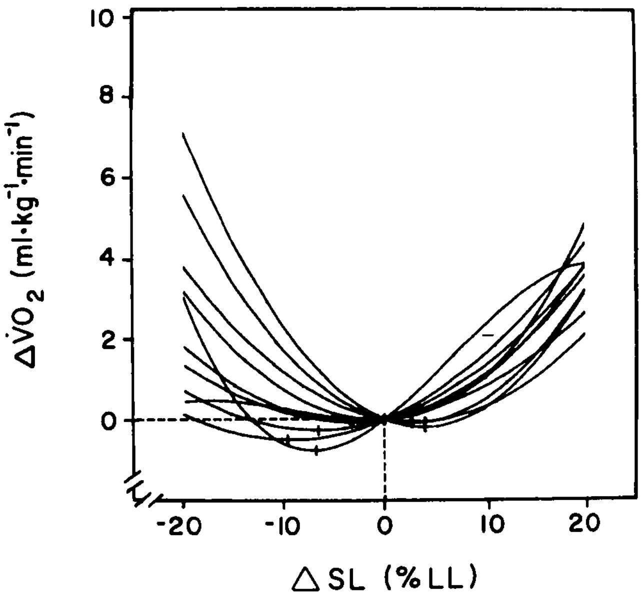

Figure 4—Best-fit curves for all subjects plotted, in terms of change in oxygen uptake and stride length from the chosen conditions. Data from eight subjects were best fit by quadratic equations and from two subjects by cubic equations.

length and oxygen consumption values given in the table have been obtained from the best-fit curves. In order to demonstrate basic similarities in the data, despite the considerable individual differences, the change in oxygen uptake from that at the chosen stride length was plotted as a function of the change in stride length from that at the chosen value.

The data from Figure 2 for subjects 2 and 6 are redrawn in Figure 3 in these relative terms to indicate the transformations made in the data. This presentation forces the curves through the point (0,0) which represents the freely chosen conditions. Stride lengths shorter than the chosen are shown as negative changes in stride length and O_2 uptake values less than chosen also appear as negative values. Similar plots for all subjects are shown in Figure 4.

The average predicted optimal stride length expressed as a multiple of leg length (SL[%LL]) was 1.40 with considerable variability among subjects (range=1.30-1.65). Low correlations were found between oxygen consumption at optimal conditions and SL ($r=0.41$) and SL(%LL), ($r=0.27$). A comparison of leg length vs optimal stride length showed a surprising correlation of -0.44, but this value was greatly influenced by extreme data from subject 2, who had the longest legs and the shortest stride, and subject 10, who had the shortest legs and a very long stride. Removing the data from these two subjects yielded a very low correlation of 0.09, indicating that there was no consistent relationship found between LL and optimal SL. Similar results for all of these comparisons were found when chosen conditions were considered instead of optimal conditions.

DISCUSSION

In considering the relevance of the results of these experiments to normal overground (OG) running, possible differences between the mechanics of OG and treadmill (TM) running must be considered. Winter et al. (14) have shown that a significant power flow exists between subject and treadmill during walking and it is reasonable to assume that the same situation occurs during running. These interactions may affect the metabolic response to a given nominal work load on the treadmill and result in a different $\dot{V}O_2$ for OG and TM running at the same speeds regardless of differences due to factors such as wind resistance (11). Variations in kinematics have, in fact, been observed between OG and TM running (5). In discussing the results of this study, the assumption is made that deviations from optimal stride length observed on the treadmill are representative of those found during OG running.

The oxygen uptake at the subjects' chosen SL show, in general, a remarkably small deviation from the predicted optimal value with a mean absolute deviation of only 0.2 ml·kg^{-1}·min^{-1}. Despite this small difference in oxygen uptake, the mean absolute difference between chosen and optimal SL is 4.2 cm or 4.5% of leg length (see Table 1). This reflects the fact that most of the curves have a relatively flat portion in the region of the minimum indicating that small changes in stride length do not have a major effect on the oxygen uptake. Even though the deviations from the optimal points were small, it is interesting to note that seven of the 10 subjects were using stride lengths longer than optimal, while only three were understriding. This is highlighted in Figure 5 where the

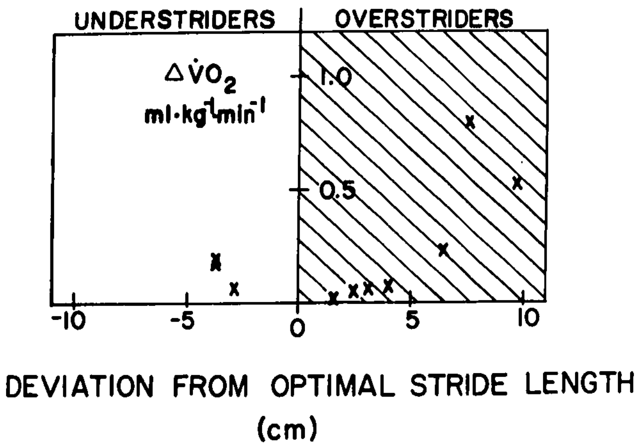

Figure 5—Variations in oxygen consumption resulting from deviations of chosen SL from the predicted optimal SL. The increased O_2 cost due to non-optimal conditions were on average small (0.2 ml·kg^{-1}·min^{-1}) despite reasonably large (4.2 cm) deviations from optimal stride lengths.

oxygen uptake and SL at the chosen value are shown in terms of their deviations from the optimal values. This figure further emphasizes the degree of similarity between optimal and chosen conditions in most of the subjects studied.

The range of optimal stride lengths found within the group of subjects was large both in absolute units and when expressed relative to leg length. The low correlations between optimal stride length (both SL and SL[%LL]) and leg length indicate that it is not in general possible to predict optimal stride length in a population of runners on the basis of leg length. The lack of a clear relationship between SL and LL is somewhat surprising since one might intuitively expect that runners with longer legs would be best suited by longer strides. Although predictive equations for optimal stride length do not appear feasible, the technique described in this paper could be applied to individual runners in order to determine whether or not a change in SL should be recommended.

From the curves shown in Figure 4, it is evident that the effects of shorter or longer than usual stride lengths on $\dot{V}O_2$ vary considerably among individuals. This is in contrast to Högberg's statement that an increase in SL above the freely chosen one gives a larger increase in $\dot{V}O_2$ than a corresponding shortening of the stride (4). The basis for the variation in individual responses appears to be related to a subject's SL(%LL), as evidenced by correlations found between SL(%LL) and the increment in $\dot{V}O_2$ above chosen conditions at both the shortest stride ($r=-0.69$) and the longest stride ($r=0.42$). This is illustrated in Figure 2. Subject 2, who has long legs and a short stride and an SL(%LL) value of 1.26, shows greater $\dot{V}O_2$ increases at shorter stride lengths. This is in contrast to the pattern of greater oxygen cost at longer strides seen for subject 6 who has an SL(%LL) value of 1.47.

The major implication of the results of this investigation is that well-trained runners are likely to run with a combination of SL and SF which is extremely close to their optimal condition. Two possible mechanisms may account for this phenomenon. First, the subjects may have used an iterative approach to the location of the optimal point, using perceived exertion to generate feedback concerning their location on the SL vs $\dot{V}O_2$ curves. Ratings of perceived exertion have been shown to be linearly related to work intensity as well as to physiological measures such as heart rate or oxygen consumption (1). It may be that during the course of a training run, or over periods of weeks of training, a runner is able to perceive physiological differences that result from variations in stride length at a given pace. This could be the result of either random alterations of stride length or as the results of intentional or subconscious experimentation.

A second possibility is that the subjects have adapted through training to the particular combinations of SL and SF which appear to be optimal for their current running styles. It may be that the optimal conditions for an individual can be changed by a prolonged period of training at a stride length which differed considerably from the optimal value. It is not possible to distinguish between these two alternatives on the basis of the present research. It would also be of considerable interest to replicate this study with a group of beginning runners to determine if their deviation from the optimal conditions is greater than the group of well-trained or experienced runners used in this study.

From a practical point of view, the results would seem to confirm the notion that the coach is, in general, wise in not dictating a particular SL profile to an athlete. This is emphasized by the lack of strong relationships between stride length and oxygen uptake or stride length and leg length. The relatively small changes in $\dot{V}O_2$ which accompany considerable variations in SL appear to indicate that SL is not a critical determinant of physiological efficient running as measured by oxygen uptake in well-trained runners. In isolated cases, however, quantitative information such as that presented in this paper, could be of definite assistance in reducing $\dot{V}O_2$ during running. As indicated in Figure 5, two subjects showed relatively large deviations from their optimal SL which resulted in an elevated oxygen uptake of 0.5 and 0.8 ml·kg^{-1}·min^{-1}. It is likely that adjustments to their stride patterns would result in significant reductions in $\dot{V}O_2$, and most likely, an improved performance in these two subjects. If, for example, subject 7 were to run a marathon (42 km) at his chosen SL at the test speed of 3.83 m·s^{-1}, he would consume approximately 10 l of oxygen more than would be required at the optimal SL. In performance terms, from the saving of this amount of O_2 cost by running at the optimal stride length, a predicted improvement of over 3 min could result, ignoring other changes which may result from the altered SL.

It is likely that the differences between an efficient runner and an inefficient one are extremely subtle and diverse in their mechanical causes. The mean absolute deviation from optimal oxygen uptake of 0.2 $ml \cdot kg^{-1} \cdot min^{-1}$ found in the present study represents a mean inefficiency of 0.5%. It may be possible in the future to identify a large number of factors similar to SL which affect physiological efficiency at a similar magnitude. The combination of these various factors could result in a large decrease in $\dot{V}O_2$ even though the individual contributions are small. The identifications of other factors in running style which affect efficiency must await a study in which a large number of biomechanical variables are systematically examined for their effect on oxygen uptake.

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