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Mechanical efficiency in athletes during running

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The purpose of this study was to compare the external mechanical efficiency (ME) between power-trained athletes ($n=5$) and endurance- trained athletes ($n=5$). The relationships between biomechanical variables and metabolic cost were also investigated. The subjects ran at 3 different speeds (2.50 $m \cdot s^{-1}$, 3.25 $m \cdot s^{-1}$ and 4.00 $m \cdot s^{-1}$) both on the treadmill and on the track. The external work of the subjects was determined by a kinematic arm, and energy expenditure was determined by measuring oxygen consumption and respiratory exchange ratio. Biomechanical parameters included ground reaction forces, angular displacements of the knee and ankle joints and electromyography (EMG) of the selected muscles. The mean ME (±SD) values during running on treadmill were as follows: 49.6±8.9%, 60.1±9.6% and 61.2±10.4% for the endurance group, and 47.1±3.7%, 52.0±4.3% and 57.4±5.5% for the power group. In running on the track the respective values were 57.5±11.9%, 51.5±6.1% and 62.2±9.2% for the endurance group, and 47.0±8.3%, 45.3±10.2% and 60.0±5.9% for the power group. The subject groups did not differ significantly in ME due to high interindividual variance among both subject groups. The metabolic responses such as heart rate, pulmonary ventilation and oxygen uptake differed clearly between the athletic groups but this was not the case for the most of the biomechanical variables (such as EMG, step length and vertical displacement of the centre of the gravity). In conclusion, physiological and biomechanical variables appear to affect ME in a very complex way. In other words, efficiency is related individually to the sum of many variables.

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Key words: running; mechanical efficiency; electromyography

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Running is economical when the energy expenditure is small compared with the distance covered. After Fenn (1), several cross-sectional studies have been published on inter- and intraindividual differences in running economy (2–5) determined as "the submaximal oxygen uptake per unit body weight required to perform a given task" (6). The intraindividual variation in running efficiency, defined as the ratio between the mechanical work and energy expenditure, varies reportedly between 3% and 11% (7, 8). In the interindividual comparison, subjects trained in endurance running are more economical than their untrained or less trained counterparts (9, 10). These differences are, however, quite small (5–7%) (11, 12).

The energy demands for submaximal running can be quantified by measuring the steady-state oxygen uptake ($\dot{V}_{O_2}$) and the respiratory exchange ratio (34). The existence of the steady-state condition (aerobic work) has been verified by the lack of blood lactate (35) and the presence of respiratory exchange ratio of less than 1.00 (2). At low and moderate work rates, the steady-state condition can be achieved within 3 min (36). At different constant speeds, the relationship between steady-state oxygen uptake and running velocity has been observed to be linear up to the point where oxygen uptake reaches a plateau (9, 11, 21, 37).

In addition to the physiological variables, the mechanical variables may be expected to influence ME as well. Total mechanical work during constant speed of running can be divided into two components: 1) external work (W_{ext}) is the sum of the work required to accelerate the center of gravity of the whole body and the work done against gravity, and 2) the work done in moving the limbs around the center of gravity of the body is called internal work (W_{int}). It has been shown that W_{ext}/km decreases with speed (38), whereas W_{int}/km increases with speed (3). Furthermore, in running the internal mechanical power is lower than the external one up to about 5.5 $m \cdot s^{-1}$, whereas at the highest speeds it is on the contrary (3).

Depending on the methods used to calculate mechanical work and energy expenditure (7, 13–17) as well as on the running speed (3, 18, 19), the mechanical efficiency (ME) in running has varied enormously. In addition, various other physiological and environmental factors such as age (20), sex (9), air resistance (21–23), body temperature (24), body weight (25, 26), maximal aerobic power (27) and muscle fiber distribution (28) have been noticed to influence running economy or efficiency. Thus, numerous investigations have been published on the physiological aspects of running efficiency. Less research is, however, available concerning how the descriptors of running mechanics affect efficiency. Nevertheless, it has been suggested that biomechanical factors may account for a substantial portion of variations of running efficiency. As compared with a less successful runner, a faster endurance runner is characterized by less vertical oscillations (29), longer strides (30, 31), less change in velocity during the ground contact (32), and lower first peak in the vertical component of the ground reaction force associated with a tendency to have smaller anteroposterior peak forces (33). Despite these observations, the interaction between the biomechanical and physiological factors is not well-known.

The purpose of the present study was therefore to investigate ME and its relationship to biomechanical and physiological variables among athletes during submaximal running at different speeds on the treadmill and on the track. It was assumed that subjects with different backgrounds in training as well as in maximal physical performance may also differ in ME in running on track and treadmill conditions.

Methods

Subjects

Five power-trained athletes (jumpers and sprinters) and 5 endurance-trained athletes (endurance runners and cross-country skiers) accustomed to regular running training volunteered as subjects for the study. Table 1 shows the physical characteristics of these two groups. For obtaining reference values of physical performances of the subjects, maximal isometric strength of bilateral leg extensors (39) and plantarflexor muscles (40) in voluntary condition (MVC), maximal oxygen uptake ($\dot{V}_{O_2max}$) with progessively increased load and maximal running speed (v_{max}) were measured (Table 2). All the subjects were fully informed of the procedures and possible risks of the experiment.

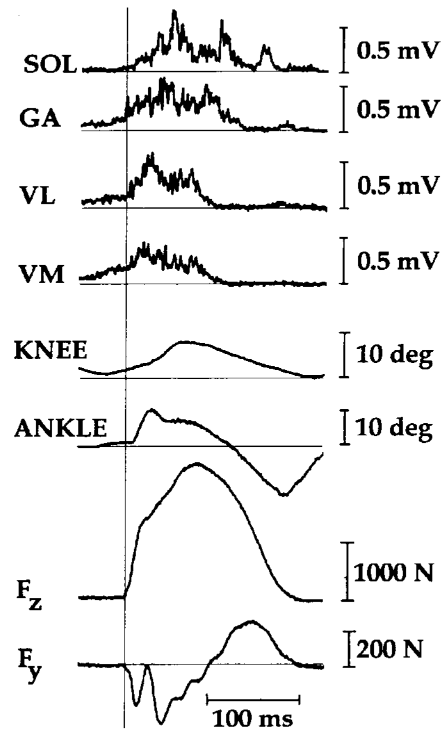

Fig. 1. The recorded biomechanical variables in running at the speed of 4.00 $m \cdot s^{-1}$ on the track. EMGs were recorded from the soleus (SOL), gastrocnemius (GA), vastus lateralis (VL), and vastus medialis (VM) muscles. Simultaneously, angular displacements of the knee and ankle joints, and vertical (F_z) and horizontal (F_y) ground reaction forces were recorded as well.

Measurements

During submaximal tests, the subjects ran for 5 min at 3 predetermined constant speeds of 2.50 $m \cdot s^{-1}$, 3.25 $m \cdot s^{-1}$ and 4.00 $m \cdot s^{-1}$ on the treadmill. A week later, the same subjects ran at the same speeds on the track. Recovery times between the running sessions lasted until the oxygen consumption had returned to the resting level.

The submaximal running tests on the treadmill consisted of measurements of biomechanical and physiological variables. Contact times were measured by special transducers (threshold of 10 N) placed inside the shoes extended under the whole sole. The velocity of the treadmill was measured by means of an optical encoder. The external work of subjects was recorded by a kinematic arm, which is a device for 3-dimensional recording of human movement. It consisted of 4 rigid bars linked together by 3 joints equipped with optical transducers. One end of the kinematic arm was connected to a fixed reference point while the other end, which was fixed to the back of the subject and near by the center of the gravity of the whole body, could move freely in the three spatial directions. For more details of this method, see Belli et al. (41).

Angular displacements of the knee and ankle joints were measured by electrogoniometers, which were attached to the lateral side of both joints of the right leg. Electromyographic (EMG) activity was recorded telemetrically (Glonner) with surface electrodes (Beckman miniature skin electrodes, 650437) from the vastus lateralis (VL), vastus medialis (VM), gastrocnemius (GA), soleus (SOL) and tibialis anterior (TA) muscles. The electrodes were placed longitudinally over the muscle bellies. The signals of horizontal and vertical ground reaction forces, angular displacement, and EMGs were stored simultaneously on a computer and on a magnetic tape. The sampling frequency in the subsequent analysis was 1000 Hz per channel. Blood samples were taken from a finger tip for lactate analysis at rest and 2 min after each testing condition.

During running at 3 submaximal speeds on the track, the running velocity and the mechanical work were measured by the same method as on the treadmill. The measuring equipment was placed in an electric car, which was driven on the side of the subject. The running speed of the subject was paced by the driver of the car. He drove around the 200-m-long track at the predetermined constant speed by following the pointer of a speedometer, which was connected to the optical encoder. The expired air for 1 min was collected into the Douglas bag during the period of the steady-state oxygen uptake (from 4 to 5 min or in some cases from 3 to 4 min). The volume of air in the Douglas bag was determined by a gasometer, and its concentrations of O_2 and CO_2 with the same gas analyzer as in the treadmill running. Angular displacements of the knee and ankle joints as well as EMGs were measured by the same methods mentioned earlier. In addition, ground reaction forces were measured by a long (13-m) force platform during every lap of 200 m. Fig. 1 demonstrates as an example the signals of ground reaction forces, EMGs and electrogoniometers stored simultaneously.

The $\dot{V}_{O_2max}$ test was performed on the treadmill with progressively increased load. During the first minute of the test the speed was 2.75 $m \cdot s^{-1}$, and the inclination of the treadmill was 1° in respect to the horizontal line. The subsequent minutes were run at the speeds of 3.25 $m \cdot s^{-1}$, 3.75 $m \cdot s^{-1}$, 4.25 $m \cdot s^{-1}$ and 4.75 $m \cdot s^{-1}$. Thereafter, the slope of the treadmill was increased (2.3°, 3.5°, 4.2°, 4.9° and 5.6°) until the subject was exhausted. The expired gases were determined by measuring pulmonary oxygen uptake, the volume of the air, and its concentrations of O_2 and CO_2 by using an semiautomated gas analyser (Oxygon Mijnhardt-4). The instrument was regularly calibrated with known gas mixtures, and the measured values were corrected in STPD. The heart rate was determined from the recordings of electrocardiographic (ECG) signals measured during the running.

The maximal running speed of the subjects was measured on the track. They ran maximally 20 m (flying 20 m) through two photocells, having individually chosen acceleration distance, and using the same shoes as in other parts of the experimental procedure of the present study. Ground reaction forces were measured by a long (13-m) force platform located in the middle of the photocells. Angular displacements of the knee and ankle joints and EMGs of the VL, VM, GA, SOL and TA muscles were measured as described earlier in this article.

Table 1. Physical characteristics of the subjects (mean SD). Fat% was determined according to the method of Jackson & Pollock (55).

	Endurance group (*n*=5)	Power group (*n*=5)
Age (years)	26±5	24±5
Height (m)	1.78±0.01	1.82±0.06
Body mass (kg)	69.9±5.0	76.8±6.4
Fat%	4.5±0.4	4.3±1.6

Analysis

In running, forces, angular displacements and EMGs were analyzed by dividing the ground contact first into braking and push-off phases according to the orientation of the horizontal force (42). EMG activities were then full-wave rectified, integrated (IEMG) and time normalized for 1 s in 4 different phases: preactivation from 100 ms to 50 ms before the contact, preactivation from 50 ms before the contact to the beginning of the contact, eccentric phase and concentric phase. The vertical force signal (F_z) was used to identify the beginning and the end of the contact. The electrogoniometer records of the knee joint were used to identify the end of the eccentric phase of the VL and VM muscles, while the SOL and TA muscles were divided into the eccentric and concentric phases according to the ankle joint. The eccentric phase of the GA was identified according to the formula of Grieve et al. (43).

Calculations of mechanical efficiency (ME)

On the treadmill the oxygen uptake ($\dot{V}_{O_2}$), the carbon dioxide production ($\dot{V}_{CO_2}$) and respiratory exchange ratio ($R = \dot{V}_{CO_2} \cdot \dot{V}_{O_2}{}^{-1}$) were measured every minute. Measurements were made before the exercise (rest $\dot{V}_{O_2}$ a in sitting position), during the exercise and during the recovery period. The rest $\dot{V}_{O_2}$ was subtracted from the total (exercise and recovery $\dot{V}_{O_2}$) oxygen consumption. To calculate the energy expenditure, an energy equivalent of 20,180 J per liter of oxygen was applied when R was 0.82. The change of ±0.01 in R value caused the respective ±42 J change in energy expenditure (44). On the track, the energy expenditure was calculated by the respective methods from the expired air of one minute. However, the same individual rest $\dot{V}_{O_2}$ value and respective individual kinetics of energy expenditure were utilized for calculating net energy expenditure as in the test on the treadmill. Increases of lactate level among the power group were ignored in every condition when calculating energy expenditure. This is based on the suggestion that "even large increases of lactate (10 mM above resting) in a relatively short time (5 min) in terms of energy equivalent represent rather minor quantities" (45).

The external mechanical energy level was calculated in y, and z directions as follows:

$$PE_{arm} = m \cdot g \cdot z_r,\ KE_{arm} = 0.5 \cdot m \cdot x_r^2 \qquad (1)$$

where PE_{arm} is the potential energy level, KE_{arm} is the kinetic energy level, EE_{arm} is the external energy level, m is the mass at the subject, g is the gravity, z_r is the vertical displacement of the centre of the mass (CM), x_r is the horizontal velocity of the CM (41). In contrast to walking, during running the potential and kinetic energy changes of the center of mass are in phase (38). This was checked to be the case also in the present study. Therefore, the work is obtained by the maximal differences between energy levels of each step as follows: $W_p=\Delta PE$, $W_k=\Delta KE$, and $W_{tot}=W_p+W_k$. Thereafter, ME was calculated by dividing the mechanical work (W_{tot}) by the energy expenditure (ΔE) above the resting level:

$$ME = \frac{W_{tot}}{\Delta E} \cdot 100\% \qquad (2)$$

The main problems associated with this equation is that stored mechanical energy (elastic energy), the multi-joint action of some muscles, and co-activation of agonist and antagonist muscles cannot be taken into consideration (46). The strict mechanical approach assumes that the sources of mechanical energy are fully intercompensated and recuperative, which is not the case for the contractile component of the muscle. Furthermore, Martin et al. (47) have recently demonstrated that, in running, the interrelationship between the aerobic demand and mechanical energy estimates was the highest when the center of mass model with nonrecuperative sources was employed.

Statistical analysis

Multivariate analysis of variance (MANOVA) for repeated measurements was utilized to test the main effects of repetitions, experimental conditions and subject groups as well as all their combined effects on every measured variable. It revealed that the repetition had no statistically significant influence on any main variables. Therefore, in running on the treadmill, the signals of 30 steps were averaged within the subject at each running speed. During running on the track from 9 to 17 contacts were averaged. Mean, standard deviation (SD) and standard error (SE) were calculated by groups and by conditions. Finally, correlation coefficients between different variables were calculated both separately in every experimental condition and in all conditions together. Statistical significance is indicated as follows: *** $P<0.001$, ** $P<0.01$, * $P<0.05$.

Results

In any submaximal running conditions, ME did not differ significantly between the subject groups. Fig. 2 demonstrates that ME did not change with increasing running speed on the treadmill among either subject groups. The endurance athletes ran, however, relatively faster and with relatively lower oxygen uptake as compared to their power type counterparts (Fig. 2, 3). Furthermore, among power athletes ME was higher, the shorter the contact time ($r=-0.79$, $P<0.01$) in the treadmill running. In running on the track, the lowest mean ME was achieved at the speed of $3.25\ m \cdot s^{-1}$ among both subject groups. The correlation coefficient between ME and the contact time was -0.53 ($P<0.05$) for both groups. In addition, the higher the step rate the higher the accumulation of lactate at all three measured speeds ($r=0.71$, $r=0.67$ and $r=0.52$, $P<0.01$–0.05) when power athletes ran on the track.

There were significant ($P<0.05$–0.001) differences in physiological variables between the subject groups (Table 2). Among the endurance athletes, the lactate level was almost the same after every running test. This was not the case among the power group. Their lactate level increased with increasing speed both on the treadmill and on the track. In every test condition the heart rate, pulmonary ventilation and the oxygen uptake increased more among the power group with increasing running speed as compared with the endurance group (Table 3). Furthermore, on the average across all conditions the power group used 9.7% more energy than the endurance-trained athletes. Fig. 4 demonstrates this phenomenon when the rate of energy expenditure is expressed per kilogram of body mass.

MANOVA revealed that the subject groups differed significantly ($P<0.01$) in all force parameters (average and maximal F_z, F_y and F_r) in the braking phase of the running contact. The power group produced higher braking forces (P varied from NS to 0.01) with increasing speed: for example, for the vertical direction they were 1938±297 N *vs* 1716±227 N, 2093±290 N *vs* 1909±191 N and 2164±307 N *vs* 2048±206 N. However, no differences between the

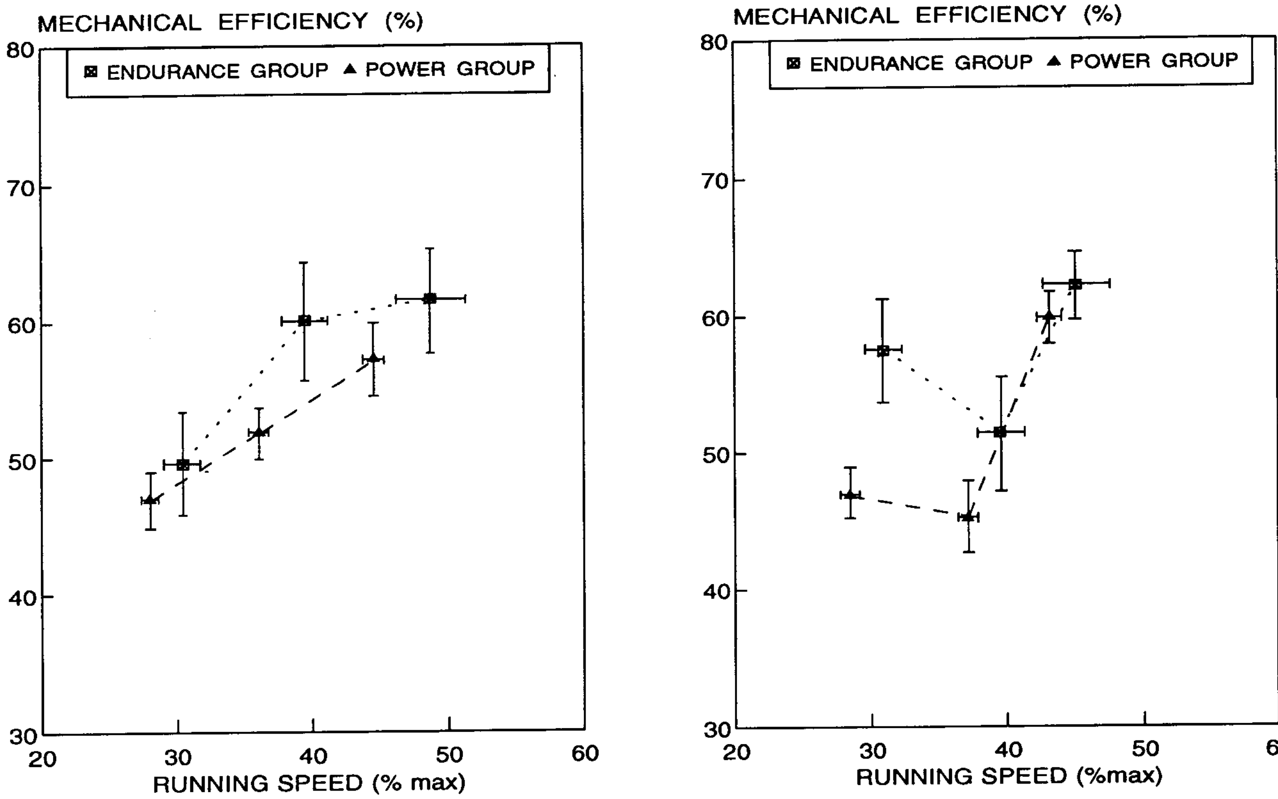

Fig. 2. The mean (±SE) values of the ME related to the the running speed on the treadmill (left) and on the track (right).

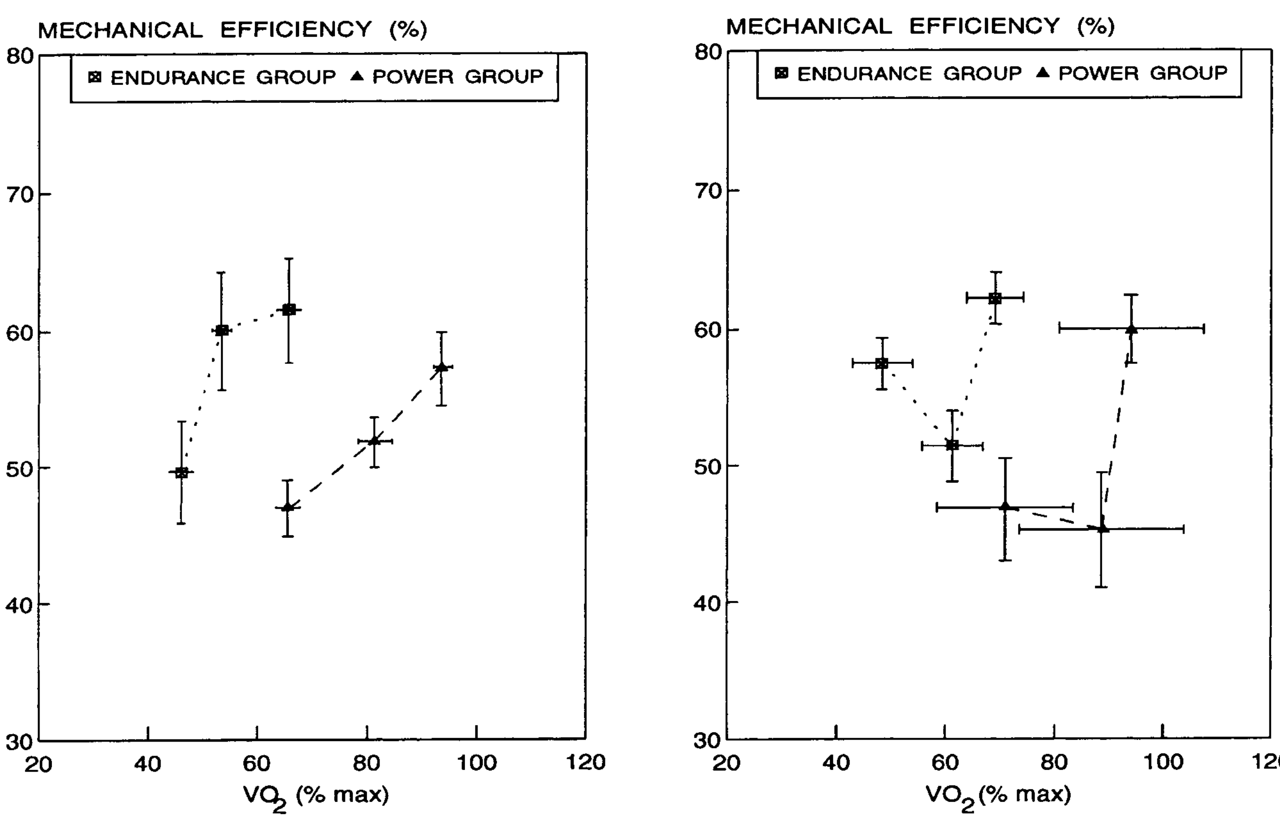

Fig. 3. The mean (±SE) values of the ME related to the relative oxygen consumption in running on the treadmill (left) and on the track (right).

Table 2. Maximal performance values of the subjects. Maximal force (F_{max}) in two isometric conditions, average velocity (v_{max}) during the maximal running of 20 m on the track, and maximal ogygen uptake ($\dot{V}_{O_2max}$) during running on the treadmill. ** $P<0.01$, * $P<0.05$.

	Endurance group	Power group
F_{max} (N) for the knee extensors	3730±700	4718±536*
F_{max} (N) for the plantarflexors	2415±353	3384±383*
v_{max} ($m \cdot s^{-1}$)	8.35±0.42	9.02±0.24*
$\dot{V}_{O_2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	72.7±3.7	54.1±4.4**

subject groups were noticed when these force values were related to the body weight of the subjects: 2.4±0.2 *vs* 2.4±0.2, 2.6±0.1 *vs* 2.5±0.3 and 2.8±0.1 *vs* 2.6±0.3, respectively. Nor did the direction of the force production differ between the groups.

Further analysis of the present study revealed that, in running on the treadmill, the endurance group had slightly shorter contact times than the power group. This difference between the subject groups was significant ($P<0.05$) in every condition when the contact times were related to their respective values during maximal running. These relative values decreased with increasing running speed among both subject groups as follows: 83.8±24.8% *vs* 131.5±18.7%, 66.9±25.4% *vs* 110.9±4.2%, and 50.5±21.7% *vs* 92.0±6.0%. Table 4 demonstrates that there were no significant differences in step rate, average angular velocity of the ankle joint in the braking phase of the contact and vertical displacement of the center of gravity of the whole body. In addition, step length, braking time, and most of the angular and force platform variables were similar between the experimental groups. However, in a few cases only the endurance group had slightly higher ($P<0.05$) average and maximal angular velocities of the knee joint in the braking phase of the contact.

The muscle activity patterns and integrated EMGs did not differ between the subject groups in any conditions (Fig. 5). This was the case both during running on track and on the treadmill. Also the relationship between the eccentric and concentric EMGs did not differ between the experimental groups.

Discussion

The major findings of the present study were as follows: 1) There were no statistically significant differences in ME between the athletic groups. 2) The metabolic responses (energy expenditure, heart rate and lactate level) differed between the subject groups, while only small differences were observed in biomechanical variables.

The endurance athletes worked all the time on aerobic level because they achieved the steady-state metabolic cost and their blood lactate values were stable at every running speeds. Therefore, no changes may have happened in their energy sources during exercise. The result of the respiratory exchange ratio (R) gives further support for this suggestion. It increased only slightly with increased running speed among the endurance group as follows: 0.79±0.04, 0.81±0.03 and 0.86±0.03 on the treadmill and 0.81±0.04, 0.85±0.02 and 0.88±0.03 on the track. The power group had higher ($P<0.05$–0.01) R values compared with their endurance counterparts: 0.88±0.04, 0.97±0.08 and 1.02±0.07 on the treadmill, and 0.88±0.04, 0.95±0.04 and 0.98±0.02 on the

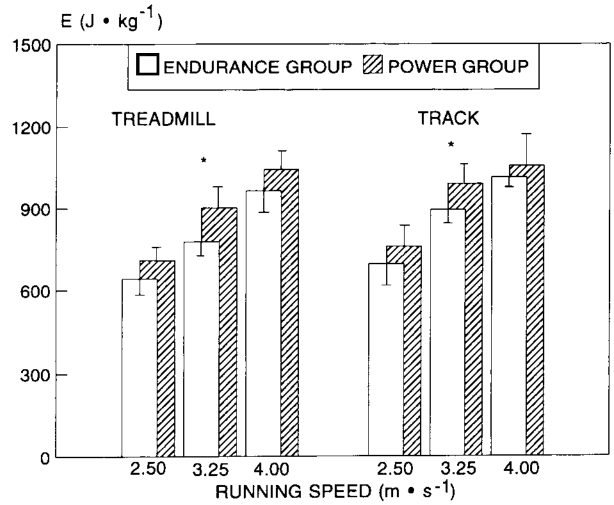

Fig. 4. The mean energy expenditure divided by the body mass in running at three different speeds on the treadmill and on the track. * $P<0.05$. The SD is indicated as −1 SD and +1SD for the endurance and power groups, respectively.

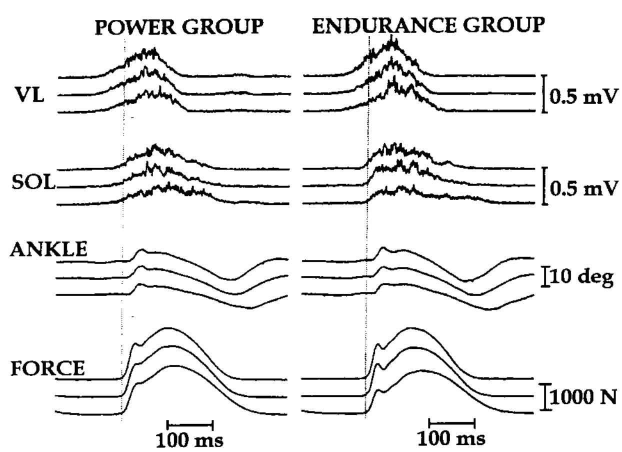

Fig. 5 Averaged signals of reaction force, ankle angle and rectified EMGs from the soleus (SOL) and vastus lateralis (VL) during the running on the track. The left curves represent a power athlete and on the right hand are the respective curves of an endurance athlete. The lowest line for every group of signals is the speed of 2.50 $m \cdot s^{-1}$, in the middle is the speed of 3.25 $m \cdot s^{-1}$ and the highest one is the speed of 4.00 $m \cdot s^{-1}$.

Table 3. Mean (±SD) of lactate (La), heart rate, ventilation (VE), relative oxygen uptake (VO_2), and relative speed in running with three constant speeds on the treadmill (upper table) and on the track (lower table) among the endurance- and power-trained athletes. *** $P<0.001$, ** $P<0.01$, * $P<0.05$.

	2.5 $m \cdot s^{-1}$		3.25 $m \cdot s^{-1}$		4.0 $m \cdot s^{-1}$	
	Endurance	Power	Endurance	Power	Endurance	Power
La ($mmol \cdot l^{-1}$)	1.18±0.32	2.14±0.75*	1.25±0.30	3.05±1.03*	1.64±0.41	5.70±1.63**
Heart rate ($beats \cdot min^{-1}$)	118±10	151±15**	134±7	172±11**	153±6	184±8***
VE ($l \cdot min^{-1}$)	37.3±4.5	56.8±4.1***	44.3±5.2	80.0±8.5***	56.1±6.2	107.3±3.0***
%$\dot{V}_{O_2max}$	46.2±4.7	65.5±4.6***	53.5±3.5	81.2±6.9***	65.7±4.3	93.5±2.9***
La ($mmol \cdot l^{-1}$	1.12±0.19	2.57±1.10*	1.10±0.07	4.25±2.26*	1.46±0.29	6.67±2.88*
Heart rate ($beats \cdot min^{-1}$)	118±9	147±15*	136±7	165±9***	152±7	177±6***
VE ($l \cdot min^{-1}$)	42.8±4.5	63.8±7.6**	56.0±3.3	93.6±15.8**	67.2±6.9	109.0±14.9**
$\dot{V}_{O_2max}$	48.2±6.4	70.9±9.7**	61.3±5.1	88.9±11.4**	69.0±3.5	94.0±10.1**
%running speed max	30.1±2.3	27.7±0.8*	39.1±2.9	36.1±1.0*	48.1±3.6	44.4±1.2*

Table 4. Mean (±SD) step rate, contact time, average angular velocities ($\bar{\omega}$) of the knee and ankle joints in the braking phase of the contact and vertical displacement of the center of the gravity of the whole body (C.M.) during one step in meter in running with different speeds on the treadmill (upper table) and on the track (lower table) among the endurance- and power-trained athletes. * $P<0.05$.

	2.5 $m \cdot s^{-1}$		3.25 $m \cdot s^{-1}$		4.0 $m \cdot s^{-1}$	
	Endurance	Power	Endurance	Power	Endurance	Power
Step rate (Hz)	2.69±0.06	2.68±0.10	2.70±0.06	2.70±0.10	2.86±0.07	2.84±0.17
Contact time (ms)	213±20	231±19	194±20	211±4*	175±16	192±6
$\bar{\omega}$ of the knee joint in the braking phase ($deg \cdot s^{-1}$)	305±78	276±64	379±71	337±56	462±64	367±35*
$\bar{\omega}$ of the ankle joint in the braking phase ($deg \cdot s^{-1}$)	166±32	197±59	198±65	231±52	240±75	263±63
Vertical displacement of C.M. (m)	0.097±0.014	0.105±0.008	0.104±0.014	0.109±0.008	0.098±0.010	0.106±0.011
Step rate (Hz)	2.60±0.07	2.59±0.10	2.69±0.09	2.65±0.13	2.72±0.10	2.74±0.14
Contact time (ms)	283±22	288±20	247±12	247±15	223±11	229±12
$\bar{\omega}$ of the knee joint in the braking phase ($deg \cdot {}^{-1}$)	296±59	246±96	408±97	292±74	442±110	325±91
$\bar{\omega}$ of the ankle joint in the braking phase ($deg \cdot s^{-1}$)	204±61	168±61	230±69	212±74	244±85	221±65
Vertical displacement of C.M. (m)	0.093±0.023	0.100±0.015	0.096±0.022	0.101±0.015	0.098±0.014	0.093±0.015
Average net F_2 (N)	656±134	798±179	818±111	926±178	932±133	983±186

track. One power subject had the R value over 1.00 at the speed of 3.25 $m \cdot s^{-1}$, and 3 of them at the speed of 4.00 $m \cdot s^{-1}$ during running on the treadmill. In general, the conditions of the present study were mostly aerobic. For the power group, however, the work at the lowest speed was certainly on an aerobic level, but at higher speeds on the treadmill, there could have been anaerobic energy expenditure during their running (Table 3). If so, their true energy cost have been underestimated and, therefore, their ME values are overestimated at the two highest speeds.

The literature is not uniform regarding ME values at different running speeds. In addition to a more general view that ME increases as running speed increases (3), there are also contrary results. Kaneko et al. (34) reported that efficiency values could actually decrease as running speed increases. Later Kaneko (48) explained that "this discrepancy was not due to physiological factors but rather to an artifactual factor related to net energy cost". More specifically, Kaneko (48) referred to the problem of the role of the anaerobic energy expenditure. This problem may be relevant for the values of the power group in the present study. In addition, it has to be emphasized that the present methods used did not take the internal work into account. It could be estimated by comparing stride length and stride frequency (49), which did not, however, differ between the subject groups in the present study. On the other hand, it has been demonstrated that total body mechanical work (external work) explains better the aerobic demands in locomotion than does segment-based model (external+internal work) (47).

In general, endurance runners have shown to have greater ME than sprinters at relatively low speeds, but this relation tended to be reverse at higher speeds (19). This difference between the two groups of runners may not be due to the calculation of total mechanical power but rather to differences in net energy cost (19). In the present study, the power athletes had a higher lactate accumulation after every running session. During exercise, they had also higher metabolic responses (Table 3), indicating that the respiratory and circulatory systems of the endurance athletes were in a better condition and/or that their oxidative energy supply was more economical and/or that they were better able to utilize the elastic energy stored in the tendomuscular system during the eccentric phase of the contact. Regarding the possible contribution of the storage and recovery of elastic energy, one faces the problem of estimating its role in the entire running cycle. It is known that ME in pure eccentric exercise increases linearly. However, this phenomenon appears to be individual with the increase of the stretching velocity (50). This is primarily due to the contribution of elastic energy. However, the condition is different in the combined stretch-shortening cycle (such as running), in which the eccentric phase is performed differently compared with the pure eccentric exercise (51).

Furthermore, in the present study, the power athletes were heavier than their endurance counterparts. This was not taken into consideration in the calculation of ME. In Fig. 4 the energy expenditure has been related to the body mass but there still exist clear differences in the energy expenditure between the subject groups. The other results have, however, shown that adding or reducing body weight has no effect on oxygen cost ($ml \cdot kg^{-1} \cdot min^{-1}$) of exercise in men (52, 53). Cureton et al. (25) have shown that extra weight has no effects on efficiency. According to the results of the present study, body mass cannot be regarded as a factor related to the observed efficiency values.

The measured biomechanical variables gave only a few additional explanations for the observed differences in energy expenditure between the subject groups. The shorter contact time and, especially, its shorter braking phase, and higher angular velocity in the same phase may increase the utilization of tendomuscular elasticity, and thus may result in greater running economy among the endurance-trained athletes.

The step length had no significant relationship with other variables among any of the subjects, who had freely chosen their running styles. However, there are studies (31, 54) that indicate that the aerobic demand of running at a given speed tends to change as the step rate, and/or the step length is changing from that freely chosen by the runner. In the present study, the step rate was related significantly ($P<0.001$–0.05) to the lactate accumulation among the power group separately in every test condition. In general, the optimal running speed is an individual characteristic associated with the step length (31, 55). Thus, the relationship between economy and biomechanical descriptors were from moderate to low, as Williams & Cavanagh (33) have also concluded.

The mean muscle activity patterns (Fig. 5) and integrated EMGs did not give any further information, which could be used to interpret the results of the present study. Therefore, no further EMG analysis was performed.

As a conclusion, ME values did not differ significantly between the subjects groups. This was the case although that the metabolic responses were lower among the endurance athletes. On the other hand, only a few of the biomechanical variables seemed to differ between the subject groups. Therefore, it is assumed that better understanding of the complex interactions between mechanical and metabolic factors can be achieved through studies emphasizing individuals instead of group comparisons.

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References

1. Fenn WO. A quantitative comparison between the energy liberated and the work performed by an isolated sartorius muscle of frog. J Physiol 1923: 58: 175–203.
2. Conley DL, Krahenbuhl G. Running economy and distance running performance of highly trained athletes. Med Sci Sports 1980: 12: 357–60.
3. Cavagna GA, Kaneko M. Mechanical work and efficiency in level walking and running. J Physiol 1977: 268: 467–81.
4. Cavanagh PR, Andrew G, Kram R, Rodgers M, Sanderson D, Hennig G. An approach to biomechanical profiling of elite distance runners. Int J Sport Biomech 1985: 1: 36–62.
5. Morgan D. Factors affecting running economy. Sports Med 1989: 7: 310–30.
6. Cavanagh P, Kram R. The efficiency of human movement – a statement of the problem. Med Sci Sports Med 1985: 17: 304–8.
7. Daniels J, Scardina N, Foley P. VO_2 submax during five modes of exercise. Bachl N, Prokop L, Suckert R, ed. Proceedings of the World Congress on Sports Medicine, Vienna, 1982. Vienna: Urban and Schwartzenberg, 1984: 604–15.
8. Morgan D, Baldini F, Martin P. Day-to-day stability in running economy and step length among well-trained male runners (abstract). Int J Sports Med 1987: 8: 242.
9. Bransford DR, Howley ET. Oxygen cost of running in trained and untrained men and women. Med Sci Sports 1977: 9: 41–4.
10. Daniels JT. A physiologist's view of running economy. Med Sci Sports Exerc 1985: 17: 332–8.
11. Margaria R, Cerretelli P, Aghemo P, Sassi J. Energy cost of running. J Appl Physiol 1963: 18: 367–70.
12. Cavagna GA, Saibene FB, Margaria R. Mechanical work in running. J Appl Physiol 1964: 19: 249–56.
13. Margaria R. Positive and negative work performance and their efficiences in human locomotion. Int Z Angew Physiol 1968: 25: 339–51.
14. Asmussen E, Bonde-Petersen F. Apparent efficiency and storage of elastic energy in human muscles during exercise. Acta Physiol Scand 1974: 92: 537–45.
15. Norman R, Sharratt M, Pezzack J, Noble E. Re-examination of the mechanical efficiency of horizontal treadmill running. In: Komi PV, ed. Biomechanics V-B. Baltimore: University Park Press, 1976: 87–93.

16. Cavagna GA. Aspects of efficiency and inefficiency of terrestrial locomotion. In: Asmussen E, Jörgensen K, ed. Biomechanics VI-A. Baltimore: University Park Press, 1978: 3–22.
17. Kaneko M, Ito A, Fuchimoto T, Toyooka J. Mechanical work and efficiency of young distance runners during level running. In: Morecki A, ed. Biomechanics VII-B. Baltimore: University Park Press, 1981: 234–40.
18. Ito A, Komi PV, Sjödin B, Bosco C, Karlsson J. Mechanical efficiency of positive work in running at different speeds. Med Sci Sports Exerc 1983: 15: 299–308.
19. Kaneko M, Ito A, Fuchimoto T, Shishikura Y, Toyooka J. Influence of running speed of the mechanical efficiency of sprinters and distance runners. In: Winter DA, Norman RW, Wells RP, Heyes KC, Patla AE, ed. Biomechanics IX-B. Champaign IL: Human Kinetics Publishers, 1985: 307–12.
20. Krahenbuhl GS, Pangrazi. Characteristics associated with running performance in young boys. Med Sci Sports Exerc 1983: 15: 486–90.
21. Pugh LGCE. Oxygen intake in track and treadmill running with observations on the effect of air resistance. J Physiol 1970: 207: 823–35.
22. Costill DL, Fox EL. Energetics of marathon running. Med Sci Sports 1969: 1: 81–6.
23. Pugh LGCE. The effect of wind resistance in running and walking and the mechanical efficiency of work against horizontal and vertical forces. J Physiol 1971: 213: 255–70.
24. Rowell LB, Brengelmann GL, Murray JA, Kraning KK, Kusumi F. Human metabolic response to hyperthermia during mild to maximal exercise. J Appl Physiol 1969: 26: 395–402.
25. Cureton KJ, Sparkling PB, Evans BW, Johnson SM, Kong UD, Purvis JW. Effect of experimental alterations in excess weight on aerobic capacity and distance running performance. Med Sci Sports Exerc 1978: 10: 194–99.
26. Karen G, Epstein Y, Magazanik A, Sohar E. The energy cost of walking and running with and without a backpack load. Eur J Appl Physiol 1981: 46: 317–24.
27. Mayhew JL. Oxygen cost and energy expenditure of running in trained runners. Br. J Sports Med 1977: 11: 116–21.
28. Bosco C, Montanari G, Ribacchi R et al. Relationship between the efficiency of muscular work during jumping and energetics of running. Eur J Appl Physiol 1987: 56: 138–43.
29. Gregor RJ, Kirkendall. Performance efficiency of world class female marathon runners. In: Asmussen E, Jörgensen K, ed. Biomechanics IV-B. Baltimore: University Park Press, 1978: 40–5.
30. Hoshikawa T, Miyashita M, Matsui H. The relationship between step-length, step-frequency, and the speed of walking or running. Res J Phys Educ 1971: 16: 157–62.
31. Cavanagh PR, Williams KR. The effect of stride length variation on oxygen uptake during distance running. Med Sci Sports Exerc 1982: 14: 30–5.
32. Kaneko M, Fuchimoto T, Ito A, Toyooka J. Mechanical efficiency of sprinters and distance runners during constant speed of running. In: Matsui H, Kobayashi K, ed. Biomechanics VIII-B. Champaign IL: Human Kinetics Publishers, 1983: 754–61.
33. Williams KR, Cavanagh PR. Relationship between distance running mechanics, running economy, and performance. J Appl Physiol 1987: 63: 1236–45.
34. Åstrand PO, Rodahl K. Textbook of work physiology. New York: McGraw-Hill, 1987.
35. MacDougall JD. The anaerobic threshold: its significance for the endurance athlete. Can J Appl Sports Sci 1977: 2: 137–40.
36. Whipp BJ, Wasserman K. Oxygen uptake kinetics for various intensities of constant load work. J Appl Physiol 1972: 33: 351–6.
37. Hill A, Lupton H. Muscular exercise, lactic acid, and the supply and utilization of oxygen. Q J Med 1923: 16: 135–71.
38. Cavagna GA, Thys H, Zamboni A. The sources of external work in level walking and running. J Physiol 1976: 262: 639–57.
39. Komi PV. A new electromechanical ergometer. In: Hauser G, Mellerowicz A, ed. 3. Internationales Seminar für Ergometrie. Berlin: Ergon-Verlag, 1973: 173–6.
40. Kyröläinen H, Komi PV. Neuromuscular performance of lower limbs during voluntary and reflex activity in power- and endurance-trained athletes. Eur J Appl Physiol 1994: 69: 233–9.
41. Belli A, Avela J, Komi PV. Mechanical energy assessment with different methods during running. Int J Sports Med 1993: 5: 252–6.
42. Mero A, Komi PV. Force-, EMG-, and elasticity-velocity relationships at submaximal, maximal and supramaximal running speeds in sprinters. Eur J Appl Physiol 1986: 55: 553–61.
43. Grieve DW, Pheasant S, Cavanagh PR. Prediction of gastrocnemius length from the knee and ankle joint posture. In: Asmussen E, Jörgensen K, ed. Biomechanics VIA. Baltimore: University Park Press, 1978: 405–12.
44. McArdle WD, Katch FI, Katch VL. Exercise physiology. Energy nutrition and human performance. Philadelphia: Lea & Febiger, 1981: 101.
45. Prampero di PE. The anaerobic threshold concept: a critical evaluation. Adv Cardiol 1986: 35: 24–34.
46. Smith R, Milburn P. A comparison of two methods of assessing mechanical energy expenditure during maximal ergometer rowing. In: Bouisset S, Métral S, Monod H, ed. Biomechanics XIV (Congress Proceedings), Paris, France, pp. 740–1.
47. MartinPE, Heise GD, Morgan DW. Interrelationships between mechanical power, energy transfers, and walking and running economy. Med Sci Sports Exerc 1993: 25: 508–15.
48. Kaneko M. Mechanics and energetics in running with special reference to efficiency. J Biomech 1990: 23: 57–63.
49. Cavagna GA, Willems PA, Franzetti P, Detrembleur C. The two power limits conditioning step frequency in human running. J Physiol 1991: 437: 95–108.
50. Aura O, Komi PV. The effects of prestretch intensity on the mechanical efficiency of positive work in natural locomotion. Int J Sports Med 1986: 7: 137–43.
51. Kyröläinen H, Komi PV, Oksanen P, et al. Mechanical efficiency of locomotion in females during different kinds of muscle action. Eur J Appl Physiol 1990: 61: 446–52.
52. Davies CTM. Metabolic cost of exercise and physical performance in children with some observations on external loading. Eur J Appl Physiol 1980: 45: 95–102.
53. Cooke CB, McDonagh JN, Nevill AM, Davies CTM. Effects of load on oxygen intake in trained boys and men during treadmill running. J Appl Physiol 1991: 71: 1237–44.
54. Kaneko M, Matsumoto M, Ito A, Fuchimoto T. Optimum step frequency in constant speed running. In: Jonsson B, ed. Biomechanics X-B. Champaign IL: Human Kinetics Publishers, 1987: 803–7.
55. Bhambani Y, Singh M. Metabolic and cinematographic analysis of walking and running in men and women. Med Sci Sports Exerc 1985: 17: 131–7.