

# Biomechanical factors affecting running economy

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## ABSTRACT

KYRÖLÄINEN, H., A. BELLI, and P. V. KOMI. Biomechanical factors affecting running economy. *Med. Sci. Sports Exerc.*, Vol. 33, No. 8, 2001, pp. 1330–1337. **Purpose:** The present study was designed to investigate kinematics, kinetics, and muscle activity for explaining running economy at different running speeds. **Methods:** A total of 17 young endurance runners ran at 12–13 different running speeds. Respiratory gases were collected. Kinematic records were obtained by a high-speed video camera, and 3-D ground reaction forces (GRF) were measured simultaneously with telemetric EMG recordings of the selected leg muscles. In the analysis, joint moments and power were calculated by inverse dynamic methods. **Results:** The oxygen consumption and energy expenditure increased quite linearly with increasing running speed. However, already at the slowest speed, interindividual differences in running economy were noticed, and they increased with increasing running speed. Simultaneously, the instantaneous joint moment-angular velocity curves of the ankle and knee joints shifted to the right and upward, thus increasing joint power in the push-off phase of contact. Most definitive was the increase in EMG-activity of the BF muscle and its correlation with energy expenditure ( $r = 0.48$ ,  $P < 0.05$ ). This two-joint muscle seems to be very active during the maximal running: its amplitude increased ( $P < 0.05$ ) both in the swinging and contact phases with increasing running speed. **Conclusions:** The increased EMG of working muscles and the associated increase in power output may partly explain the increased energy expenditure with increasing running speed. Lower performances in running economy by some of the athletes may also be explained by poor running technique, such as unusually high braking and mediolateral forces, which may be caused by limited action of the hamstring muscles. However, no exclusive biomechanical parameters could be identified to explain the running economy. **Key Words:** MOMENT, POWER, EMG, ENERGY, GROUND REACTION FORCE

Running is economical when the energy expenditure is small compared with the distance covered. In the interindividual comparison, subjects trained in endurance running are more economical than their untrained counterparts (4), whereas intraindividual variation in running economy varies reportedly between 2% and 11% (28). In addition, various physiological and environmental factors influence running economy and/or mechanical efficiency (the amount of work done as a proportion of the energy expenditure). Factors such as age (e.g., 21), sex (e.g., 4), air resistance (e.g., 9), body temperature (e.g., 32), body weight (e.g., 2), maximal aerobic power (e.g., 24), and muscle fiber distribution (e.g., 3) have been included in this discussion.

Furthermore, it has been suggested that biomechanical factors may account for a substantial portion of variations of running economy. A successful endurance runner is characterized by less vertical oscillation (15), longer strides (8), less change in velocity during the ground contact (18), and

lower first peak in the vertical component of the ground reaction force, associated with a tendency to have smaller anteroposterior peak forces (34). Despite these observations, the interaction between the biomechanical and physiological factors is not well known. Thus, further understanding of the biomechanical factors affecting running economy requires more precise estimates of the joint kinetics together with muscle actions.

Therefore, the main purpose of the present study was to explain intraindividual differences in running economy by biomechanical factors such as joint kinetics and muscle electromyographic (EMG) activity at different running speeds. Another important purpose of the present study was to investigate how running economy and its determining factors change as a function of running speed. In this regard, the EMG recordings were studied in relation to joint kinetics to interpret the possible increase in oxygen cost.

## METHODS

**Subjects.** Eight female (age  $21 \pm 3$  yr, height  $1.68 \pm 0.02$  m, body mass  $55.7 \pm 4.5$  kg, body fat  $18.3 \pm 3.0\%$ ) and nine male ( $20 \pm 2$  yr,  $1.80 \pm 0.03$  m,  $68.1 \pm 1.9$  kg, 8.9

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$\pm 1.1\%$ , respectively) middle-distance runners volunteered as subjects for the present study. They had a training background of  $7 \pm 3$  yr and had covered  $3770 \pm 1690$  km of running during the year preceding the study. All the runners were fully informed of the procedures and possible risks of the experiment, and they gave their written agreement to participate in this project, which was part of their normal testing.

**Procedure and measurements.** Subjects were asked to perform nine submaximal running bouts and four maximal sprints on an indoor track (Jyväskylä, Finland). During submaximal tests, the subjects ran for 3 min at predetermined constant speeds of  $3.25 \text{ m}\cdot\text{s}^{-1}$ ,  $4.00 \text{ m}\cdot\text{s}^{-1}$ ,  $4.50 \text{ m}\cdot\text{s}^{-1}$ , and  $5.00 \text{ m}\cdot\text{s}^{-1}$  with 3-min recovery between each exercise. After a 10-min set recovery, they ran 1 min at the constant speeds of  $5.50 \text{ m}\cdot\text{s}^{-1}$ ,  $5.75 \text{ m}\cdot\text{s}^{-1}$ ,  $6.00 \text{ m}\cdot\text{s}^{-1}$ , and  $6.50 \text{ m}\cdot\text{s}^{-1}$ , having a 5-min recovery between each exercise. Finally, after a 15-min set recovery period, the maximal speed of each subject was measured during a sprint over a distance of 30 m, the run-up phase having been individually selected by the subject. The mean ( $\pm$  SD) maximal speed was  $8.31 \pm 0.75 \text{ m}\cdot\text{s}^{-1}$  among the whole subject group. In all tests, the average speed was measured and controlled by photocells (Newtest, Oulu, Finland).

During submaximal running, the subjects ran on the right side of an electrical car, which was paced by its driver. He drove counterclockwise around the 200-m-long track at the predetermined constant speed by following the pointer of a speedometer, which was connected to a pulse meter. The gas analyzer (SensorMedics  $V_{\max}$  229, Yorba Linda, CA) was placed in the car, and the expired air was analyzed continuously utilizing the breath-by-breath method. The instrument was regularly calibrated with known gas mixtures, and the measured values were corrected in STPD. For studying the physiological loading of the subjects, the heart rate was recorded by Sport Tester (Polar Electro, Kempele, Finland). Blood samples were drawn from a fingertip for blood lactate (B-La) analysis at rest and 2 min after each testing condition.

During every lap, 3-D ground reaction forces (GRF) were measured by a 10-m-long force platform (TR-testi, Jyväskylä, Finland, and Kistler, Switzerland: natural frequency  $\geq 150$  Hz, linearity  $\leq 1\%$ , cross talk  $\leq 2\%$ ). EMG activity was recorded telemetrically (Glonner, Munich, Germany) with surface electrodes (pregelled electrodes, NI 4560, Niko, Gloucestershire, UK) from the gluteus maximus (GM), vastus lateralis (VL), biceps femoris (BF), gastrocnemius (GA), and tibialis anterior (TA) muscles. The electrodes with interelectrode distance of 38 mm were placed longitudinally over the muscle bellies between the center of the innervation zone and the distal tendon of each muscle. Because of the quite large distance between the EMG electrode pairs, the cross talk between muscles was assumed to have minimal influence on the recorded signals (35). The EMG signal amplification was 200 (Glonner Biomes 2000; cut-off frequency  $360 \text{ Hz}\cdot 3 \text{ dB}^{-1}$ ), and it was digitized simultaneously with the force records at a sampling frequency of 1 kHz.

Kinematic records were obtained by video camera (NAC, HSV-200, Tokyo, Japan), which was located 14.5 m to the right side away from the midpoint of the running track. The camera was set at a height of 1.2 m above the ground. The operating rate was  $200 \text{ frames}\cdot\text{s}^{-1}$ , and the shutter speed was set to  $1/1000$  s to ensure sharp images of the runner. The camera views, which was calibrated using  $3.0 \times 2.0$  m width and height, respectively, of calibration frame, were set to include 6.0 m of running. The frame was parallel with the track and at the midway of the optical axis of the camera.

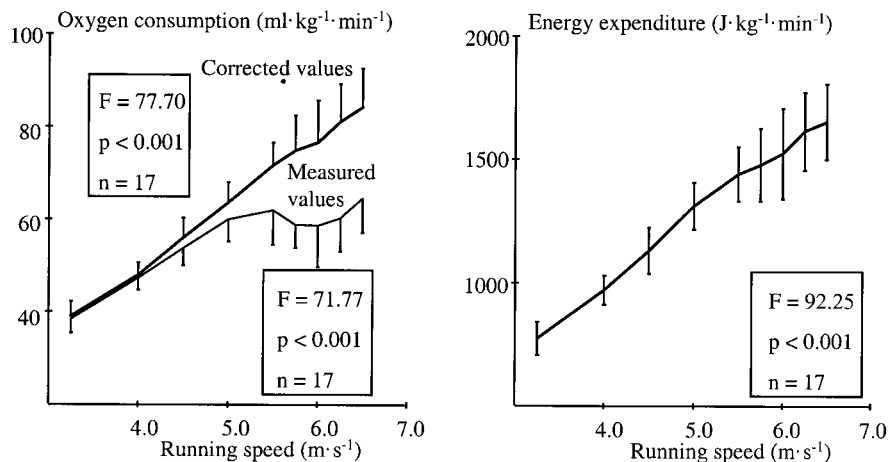
**Analysis.** In the expired air analysis, only the steady state phase of 20 s for the 3-min runs and the last 20 s for the 1-min run was taken for further analysis. To calculate the energy expenditure, an energy equivalent of 20202  $\text{J}\cdot\text{L}^{-1}$  oxygen was applied when respiratory exchange ratio (R) was 0.82. The change of  $\pm 0.01$  in R-value caused the respective  $\pm 50$  J changes in energy expenditure (25). This method was utilized when B-La was negligible ( $<2.0$  mM). When B-La exceeded the mentioned threshold, its energetic value was then calculated on the basis of an equivalent of  $60 \text{ J}\cdot\text{kg}^{-1}\cdot\text{mM}^{-1}$  ( $3 \text{ mL O}_2\cdot\text{kg}^{-1}\cdot\text{mM}^{-1}$ ) (31). Finally, this value was added to the oxygen consumption and aerobic energy cost obtained as described above. This sum value can be referred as the equivalent oxygen consumption. The heart rate values were determined by averaging their values during the respective steady state phase.

For the biomechanical analysis, three contact phases of each runner at all investigated running speeds were selected for the further motion analysis, which was synchronized with analog signals. The vertical force signal of 50 N was used to identify and trigger (flash on the video) the beginning and the end of the contact. GRFs were divided into braking and push-off phases according to the orientation of the horizontal force (27). All recorded and calculated signals were averaged intraindividually at each running speed for obtaining muscle activation patterns, 3-D ground reaction force curves, and curves of angular velocity, moment, and power of the hip, knee, and ankle joints. For further description of running strategy in several speeds, interindividual grand mean curves were drawn as well.

**Calculations of joint moment and power.** 2-D video analysis (Motus workplace, Peak Performance Technologies, Inc., Denver, CO) was used to study movements of the distal head of the 5th metatarsal bone, lateral malleolus, lateral epicondyle of the femur, greater trochanter, and tragus. The digitized body segment coordinates were transferred to the computer system (Silicon Graphics, Mountain View, CA) for further analysis. Anthropometric data provided by the standards of Dempster (11) were used to determine inertia and mass of the segments. The scaled coordinates were synchronized with 2-D GRF data for calculating joint moments and power by inverse dynamic methods (1).

**Statistics.** Multivariate analysis of variance (MANOVA) for repeated measurements was utilized to test the main effects of repetitions, gender, and experimental conditions as well as all their combined effects on selected variables. It revealed that the repetition had no statistically significant influence on any

**FIGURE 1**—Mean ( $\pm$  SD) oxygen consumption and energy expenditure with increasing running speed. Their values were corrected by the energetic values of blood lactate (31).



main variables. Therefore, all signals of each contact were averaged within the subject at each running speed. Mean and standard deviation (SD) were calculated by conditions and by sexes. Stepwise multiple regression analysis was used to examine the relationships between variables.

## RESULTS

The measured oxygen consumption increased linearly up to the speed of 5 m·s<sup>-1</sup>, whereas the equivalent oxygen consumption values increased from 2.4 to 3.8 L·min<sup>-1</sup> (from 38.4 to 60.3 mL·kg<sup>-1</sup>·min<sup>-1</sup>) with increasing running speed from 3.25 to 6.25 m·s<sup>-1</sup>. Figure 1 demonstrates that the equivalent oxygen consumption values and energy expenditure by the energy equivalent of B-La increased quite linearly with increasing running speed. In addition, interindividual differences in energy expenditure, of which values increased with increasing speed, were noticed. When the absolute oxygen consumption and energy expenditure were related to the body mass of subjects, no gender differences in these variables were observed. Table 1 shows some other physiological variables in each testing condition. Their values increased significantly ( $P < 0.001$ – $0.05$ ); however, gender differences exist in all these variables.

As expected, the contact times shortened gradually with increasing speed (from 0.227  $\pm$  0.011 s at the slowest speed to 0.115  $\pm$  0.007 s at the maximal speed,  $P < 0.001$ ). The step frequency (from 2.79  $\pm$  0.08 Hz to 4.09  $\pm$  0.19 Hz,  $P < 0.001$ ) and the step length (from 1.17  $\pm$  0.06 m to 2.03  $\pm$  0.17 m,  $P < 0.001$ ) increased again as expected. How-

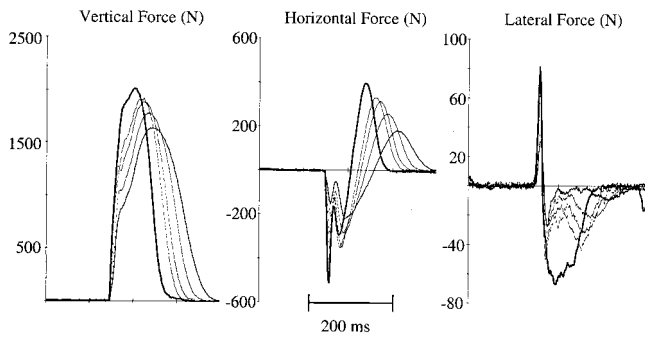
ever, contact time and step frequency did not correlate significantly with running economy.

The stepwise regression analysis revealed that the averaged horizontal force in the braking phase was the main factor (82.1%) from the 3-D force parameters to explain the oxygen consumption. Figure 2 demonstrates changes in the ground reaction forces with increasing speed. The maximal force values increased gradually from 1665  $\pm$  219 N to 2134  $\pm$  226 N ( $P < 0.001$ ) in the vertical direction and from 235  $\pm$  42 N to 675  $\pm$  173 N ( $P < 0.001$ ) in the positive horizontal direction. In the lateral forces, it was interesting to see the fast inward force of short duration in the beginning of the contact followed by a longer lasting outward force. The maximal values of lateral forces varied from 30 to 80 N inward and from 20 to 60 N outward.

Analysis of joint kinematics revealed further that the angular displacements in the ankle and knee joints during the contact phase reduced with increasing running speed (Fig. 3). At the same time, the hip extended with a larger range. The peak and average angular velocities of the ankle, knee, and hip joints increased significantly ( $P < 0.001$ ) only in the push-off phase. In the ankle joint, peak value increased from 13.2  $\pm$  1.8 to 20.9  $\pm$  3.2 rad·s<sup>-1</sup>, whereas the average value varied between 8.1  $\pm$  1.1 and 12.2  $\pm$  2.2 rad·s<sup>-1</sup>. The respective values for the knee joint increased from 4.8  $\pm$  0.1 to 8.2  $\pm$  2.1 rad·s<sup>-1</sup>, and from 2.9  $\pm$  0.5 to 5.1  $\pm$  1.4 rad·s<sup>-1</sup> with increasing running speed. The highest increase in the angular velocities, however, were observed in the hip joint: from 6.3  $\pm$  0.9 to 11.7  $\pm$  1.5 deg·s<sup>-1</sup>, and from 2.7  $\pm$  0.5 to 8.2  $\pm$  1.2 rad·s<sup>-1</sup>. In addition, the

**TABLE 1.** Mean ( $\pm$  SD) of the pulmonary ventilation ( $\dot{V}E$ ), respiratory exchange ratio (RER), respiratory frequency (RF), heart rate (HR), and blood lactate (B-La) with increasing running speed in women (W) and in men (M).

	Sex	3.25 m·s <sup>-1</sup>	4.00 m·s <sup>-1</sup>	4.50 m·s <sup>-1</sup>	5.00 m·s <sup>-1</sup>	6.00 m·s <sup>-1</sup>	6.25 m·s <sup>-1</sup>
$\dot{V}E$ (L·min <sup>-1</sup> )	W	49.8 $\pm$ 4.9	63.5 $\pm$ 8.0	79.7 $\pm$ 15.8	95.3 $\pm$ 14.7	102.3 $\pm$ 9.3	100.7 $\pm$ 12.9
	M	54.1 $\pm$ 5.2	70.2 $\pm$ 6.9	84.2 $\pm$ 9.2	101.7 $\pm$ 12.3	104.2 $\pm$ 15.3	117.9 $\pm$ 10.9
RER	W	0.76 $\pm$ 0.03	0.83 $\pm$ 0.04	0.89 $\pm$ 0.05	0.94 $\pm$ 0.06	0.78 $\pm$ 0.04	0.76 $\pm$ 0.04
	M	0.73 $\pm$ 0.05	0.80 $\pm$ 0.04	0.84 $\pm$ 0.06	0.88 $\pm$ 0.07	0.74 $\pm$ 0.02	0.77 $\pm$ 0.07
RF (L·min <sup>-1</sup> )	W	32 $\pm$ 5	37 $\pm$ 6	43 $\pm$ 7	51 $\pm$ 7	59 $\pm$ 6	60 $\pm$ 9
	M	30 $\pm$ 6	34 $\pm$ 6	38 $\pm$ 6	42 $\pm$ 6	48 $\pm$ 7	50 $\pm$ 5
HR (bpm)	W	154 $\pm$ 18	171 $\pm$ 15	182 $\pm$ 15	190 $\pm$ 13	182 $\pm$ 8	185 $\pm$ 8
	M	139 $\pm$ 13	159 $\pm$ 12	172 $\pm$ 12	182 $\pm$ 11	183 $\pm$ 6	185 $\pm$ 6
B-La (mmol·L <sup>-1</sup> )	W	3.03 $\pm$ 0.77	2.87 $\pm$ 0.68	4.50 $\pm$ 1.82	7.18 $\pm$ 3.06	9.48 $\pm$ 2.20	11.26 $\pm$ 1.98
	M	2.43 $\pm$ 0.58	2.88 $\pm$ 0.48	3.07 $\pm$ 0.83	4.56 $\pm$ 1.42	6.67 $\pm$ 2.48	7.30 $\pm$ 2.29



**FIGURE 2**—Mean curves of vertical, horizontal, and lateral ground reaction forces from the slowest speed of  $3.25 \text{ m}\cdot\text{s}^{-1}$  (thin solid line; mean of 170 contacts) up to the maximal speed (thick solid line; mean of 34 contacts). The dashed lines indicate the respective ground reaction forces at the three medium speeds (5.00, 6.00, and  $7.00 \text{ m}\cdot\text{s}^{-1}$ ). In the phase, the shortening contact time implies increases in the running speed.

instantaneous joint moment-angular velocity curves of the ankle and knee joints shifted to the right and upward (Fig. 4).

One should expect that the changes in the presented mechanical parameters are caused by muscle actions. Therefore, analysis of muscle activity patterns was performed. Most definitive was the increase in EMG-activity of the BF muscle (Fig. 5), and its correlation with energy expenditure ( $r = 0.48$ ,  $P < 0.05$ ; Fig. 6). This two-joint muscle seems to be very active during the maximal running: its amplitude increased ( $P < 0.05$ ) both in the swinging and contact phases with increasing running speed.

The GM muscle was active in the late swing and in the braking phase of contact (Fig. 5). Its amplitude increased ( $P < 0.05$ ) with increasing running speed, but the duration of its activity did not change despite the shortened contact times. In the VL muscle, quite similar increases in the EMG amplitudes with increased speed were observed ( $P < 0.001$ – $0.05$ ; Fig. 5). Its activity, however, almost disappeared early before the toe-off at every running speed. As an extensor muscle, GA behaved like the GM and VL muscles. Its activity increased in the pre- and braking phases ( $P < 0.05$ ). The TA muscle, on the other hand, increased its activity in the middle of the swing phase and slightly in the beginning of the contact ( $P < 0.01$ – $0.05$ ).

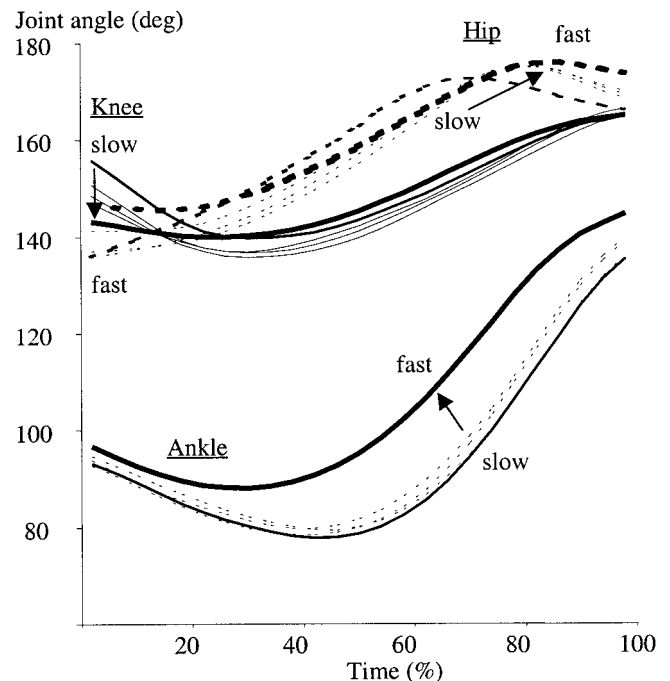
## DISCUSSION

The major findings of the present study show that with increasing running speed: 1) Oxygen consumption and energy expenditure corrected by B-La energy equivalent increased linearly. However, the most economical runners differed already at the lowest speed and this difference increased with increasing running speed. 2) Angular displacements of the ankle and knee joints decreased during the braking phase. At the same time, their instantaneous joint moment-angular velocity curves shifted to the right and upward. 3) The importance of hip extensors increased. This can be seen both in the increased EMG activity of the BF muscle and in the increased angular velocity (power output) of the hip joint. 4) Only few biomechanical variables could

explain the difference in running economy among the whole runner group. The increased braking force in the horizontal direction and increased muscle activity of the main running muscles seem to be the major explanatory factors in this regard.

In the present study, methodological problems together with the limiting physiological factors of human performance may influence the results of oxygen consumption and energy expenditure. The submaximal running tests of 1-min duration were obviously not enough to reach the highest possible oxygen consumption. Thus, the true oxygen consumption has most probably been underestimated. On the other hand, most of our subjects could not have run for 3 min at the speeds over  $5.5 \text{ m}\cdot\text{s}^{-1}$ . If they had been able to do this, it is still likely that the steady-state of  $\dot{V}O_2$  could not be reached, because the highest running speeds were certainly above anaerobic level. As the lactate turnover versus clearance can be studied only in laboratory conditions, the method of di Prampero et al. (31) was used to calculate the equivalent energy expenditure. Another methodological problem of the present study may be involved in the order of the running tests, which were not randomized. However, when progressing from the slowest speed to the maximal one, the possible fatigue effects were minimized. Thus, considering those methodological limitations, oxygen consumption and energy expenditure values at the higher running speeds should be interpreted with a caution.

The results of the present study are well in agreement with earlier findings that a runner who is economical at a given speed of running will usually be economical at other speeds as well (33), and the interactions between



**FIGURE 3**—Mean curves of angular displacements of the hip, knee, and ankle joints during the contact phase with increasing running speed from the slowest speed of  $3.25 \text{ m}\cdot\text{s}^{-1}$  up to the maximal speed. The contact phase has been time-normalized.

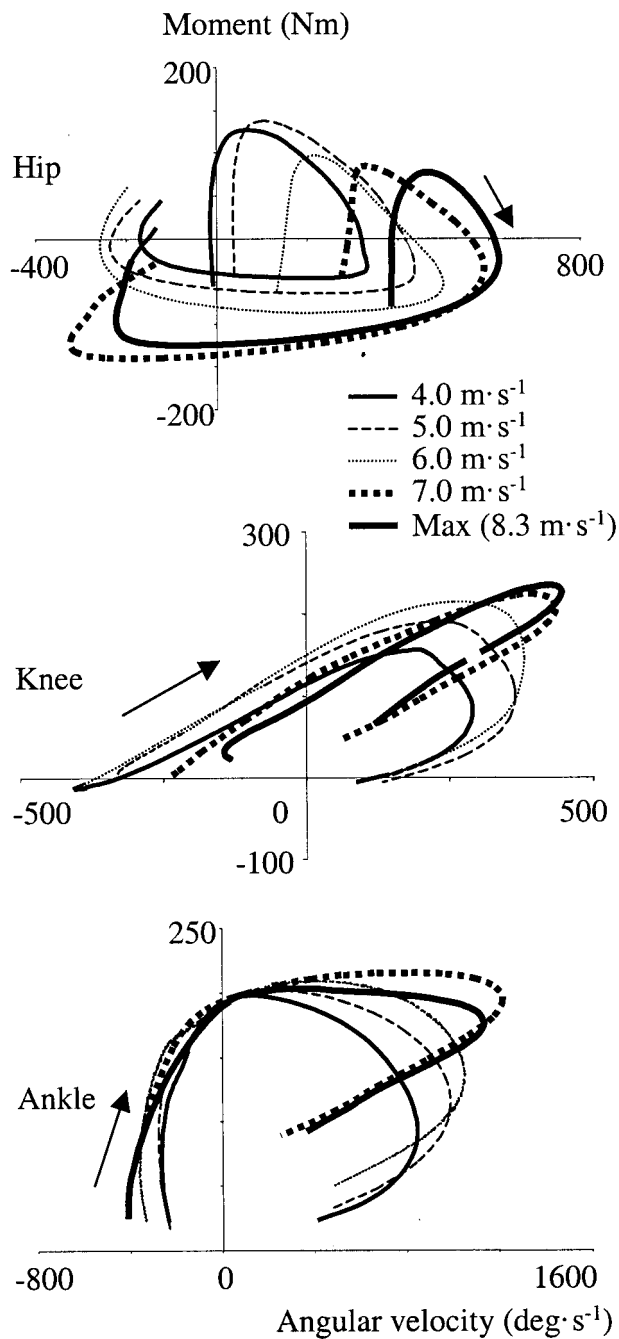


FIGURE 4—Mean instantaneous joint moment-angular velocity curves of the hip, knee, and ankle joints from the beginning of contact to the end of it (arrow) with increasing running speed from  $4.00 \text{ m}\cdot\text{s}^{-1}$  (thin solid line) up to the maximal speed (thick solid line). The dashed lines indicate the respective ground reaction forces at the three medium speeds ( $5.00$ ,  $6.00$ , and  $7.00 \text{ m}\cdot\text{s}^{-1}$ ).

mechanical and metabolic variables appear to be very complex (23,34). Furthermore, those runners who competed successfully were also the most economical in the present study. Physiological variables differed expectedly between genders, and they were also well in line with earlier literature (10). Male subjects are more economical at a given speed; however, no differences between genders were observed at the relative ( $\% \dot{V}O_{2\text{max}}$ ) intensity of running (10). The training status of the present subjects

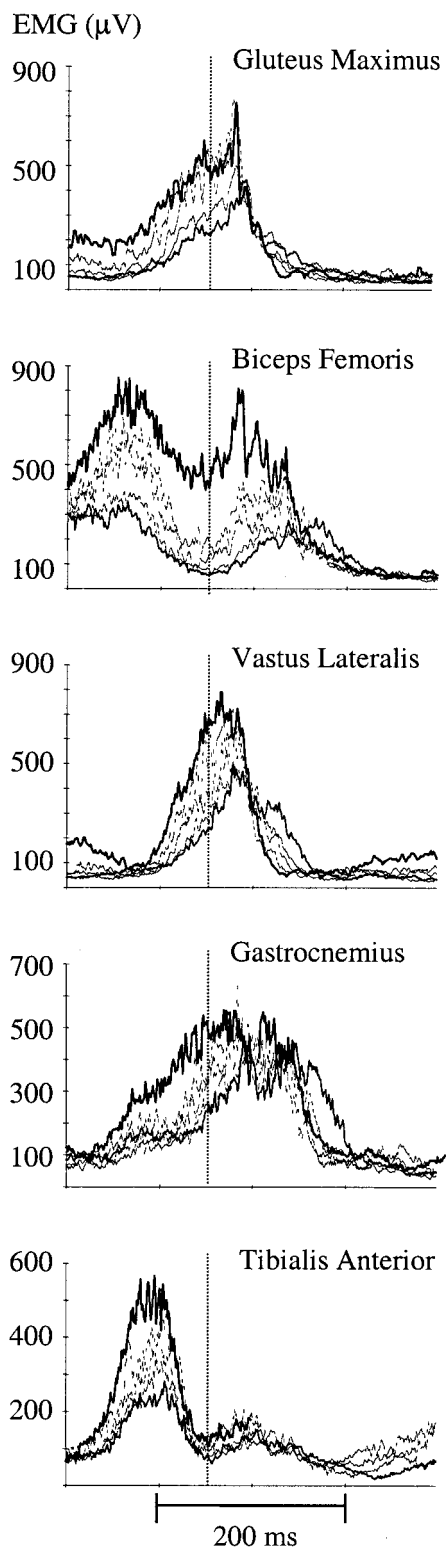


FIGURE 5—Muscle activity patterns of the gluteus maximus, biceps femoris, vastus lateralis, gastrocnemius, and tibialis anterior muscles from the slowest speed of  $3.25 \text{ m}\cdot\text{s}^{-1}$  (thin line; mean of 170 contacts) up to the maximal speed (thick line; mean of 34 contacts). The dashed lines indicate the respective EMG curves at the three medium running speeds, and the vertical lines indicate the beginning of the contact phase.

explains neither the observed interindividual difference in running economy. This is also in agreement of earlier study where 6 wk of training did not improve running

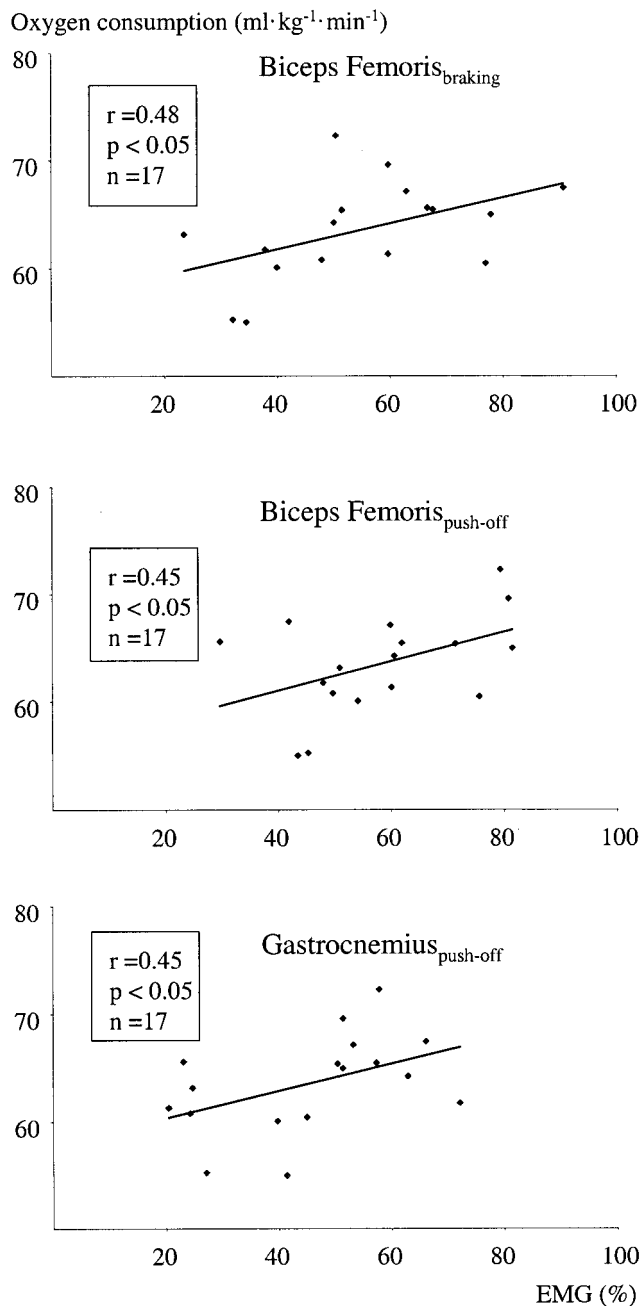


FIGURE 6—Relationships between the individual changes of the relative EMG values (EMG values are 100% at the maximal speed) of the biceps femoris and gastrocnemius muscles either in the braking or push-off phase of contact and the oxygen consumption at the submaximal running speed of  $5.00 \text{ m}\cdot\text{s}^{-1}$ .

economy (23). Thus, it is a puzzling question what are the factors in explaining differences in running economy?

The measured biomechanical variables gave only a few additional explanations for the observed differences in running economy among endurance runners. The shortening contact times and increased stride frequency associated with the increased functional contribution of stretch reflexes (12), and minor angular displacements in the ankle and knee joint in the braking phase (Fig. 3) demand greater from the function of the neuromuscular system. A short and rapid stretch with a short coupling time and a high force at the end

of prestretch creates a good precondition for utilizing tendomuscular elasticity (6,20). Thus, in the present study, stiffer muscles around the ankle and knee joint in the braking phase caused further force potentiation in the push-off phase (Fig. 7), when less increase in chemical energy expenditure among better runners may be observed. As a consequence of that, mechanical efficiency (ME) may improve although literature is not uniform regarding ME values at different running speeds. A more general view suggests that ME increases as running speed increases (5). In addition, in the present study the better and more economical runners may have higher ME values already at the lowest speeds as compared with their poorer counterparts. This might be due to their more elastic muscle structure (extracellular matrix and muscle fiber itself). Our preliminary data suggests that a role of titin is important not only in force transmission from the myosin filaments to the z-disk but also in sparing chemical energy expenditure due to its elastic structure (26).

The analysis of GRFs together with muscle actions may explain further differences in running economy. In the present study, the GRFs and their rate of force production increased with increasing running speed (Fig. 2). For tolerating higher impact loads, the increased prelanding and braking activity of leg extensor muscles might prevent unnecessary yielding of the runner during the braking phase. Thus, preactivation appears to be a preparatory requirement both for the enhancement of EMG activity during the braking phase and for timing of muscular action with respect to the ground contact. Centrally programmed prelanding activity (20) seems to be important for regulating the landing stiffness (e.g., 13) and for compensating local muscular failure (e.g., 17). Furthermore, preactivity is assumed to increase sensitivity of the muscle spindle via enhanced alpha-gamma-coactivation potentiating stretch reflexes

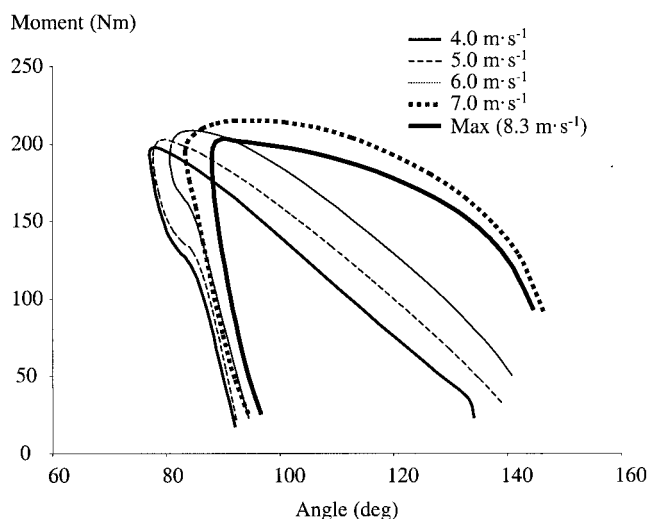


FIGURE 7—Mean instantaneous ankle joint moment-angle curves with increasing running speed from  $4.00 \text{ m}\cdot\text{s}^{-1}$  (thin solid line) up to the maximal speed (thick solid line). The dashed lines indicate the respective ground reaction forces at the three medium speeds ( $5.00$ ,  $6.00$ , and  $7.00 \text{ m}\cdot\text{s}^{-1}$ ).

(14), enhancing tendomuscular stiffness (16,30) and, therefore, economy of running (22).

In the present study, the increased coactivity of agonist and antagonist muscles (VL vs BF and GA vs TA) just before and after touch-down (Fig. 5) suggests increased knee and ankle joint stiffness in the beginning of the contact. In the late stance phase, however, the activity of leg extensors almost disappeared early before the toe-off, suggesting rebound phenomenon due to very active state of muscles in the previous phases. During preactivity (19) and braking phases, the plantarflexors and knee extensors generate actively high tension, which can be released passively during the push-off phase. As a result, joint angular velocities (Fig. 4) and power will increase and cause only slight increase in oxygen consumption of those muscles of better runners. In the maximal speed, the present runners could not, however, maintain the high angular velocities in the end of stance phase (Fig. 4). This may be due to their poor muscle coordination in the maximal speed, which was not used in their daily training.

The greatest and longer lasting change in the muscle activity of the BF muscle with increasing speed may be indicative for further force production in the contact phase when extending the hip joint. The relative lengthening of the hamstring activity during the stance phase with increasing running speed may emphasize the role of the hamstring muscles to drive the body powerfully in the forward direction. At the same time, the oxygen consumption increased linearly ( $P < 0.05$ ) with EMG activity of the BF muscle (Fig. 6).

The vertical and horizontal forces in the present study are slightly higher than in the earlier findings (e.g., 29). Their maximal values varied from 2.7 to 3.5 times body weight

(BW) and from 0.4 to 1.1 BW with increasing running speed. One might expect that running is two-dimensional movement; however, medio-lateral forces are clearly remarkable (Fig. 2). They varied from 0.05 to 0.1 BW in the present study, which is slightly smaller as compared with the values in the literature (e.g., 7). In addition, the present study demonstrated fast and short force production to the medial direction in the beginning of the contact followed by a longer lasting outward force. This might be a natural running strategy of a human being, but, of course, interindividual variability exists, affecting also running economy.

As a conclusion, the present findings are in line with those of Williams and Cavanagh (34) that the biomechanical descriptors as used in this study are not predictors of running economy. However, the present study revealed the role of the powerful force production during the ground contact. Especially important in this regard is the activation of the leg extensors during the preactivity and braking phases, and their coordination with longer lasting activation of the hamstring muscles. It may also be suggested that proper coactivations of the muscles around the knee and ankle joints are needed to increase the joint stiffness to match the requirement for increase in running speed. The action of the hip extensors becomes then beneficial during the ground contact.

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