EFFECTIVENESS AND ECONOMY IN RUNNING

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INTRODUCTION: Performance in middle-/long- distance running is mainly limited by energy expenditure. An athlete can maintain or increase his running velocity as long as he is able to supply his muscles with energy. From the biomechanical point of view, it is important to investigate how to move with high velocity at a relative minimum of energy expenditure. To answer this question it is necessary to analyze the energetics of running and to examine the ways in which the energy produced by muscular contraction is converted into mechanical work.
In view of the limiting factor of "energy expenditure", maximum efficiency of running technique corresponds to a relative minimum of "mechanical energy losses". In the analysis of running efficiency the approach to determine the relation between mechanical work and physiological energy expenditure has been most frequently pursued (Shorten, 1983; Williams & Cavanagh, 1987; Kaneko 1990) with different values of gross efficiencies, depending on the speed of running but mostly on the method of calculating mechanical power. In this context there is still no agreement about the most adequate way to estimate the mechanical power of the muscles (Aleshinski, 1986), and several authors doubt that this problem can be resolved satisfactorily (Kaneko, 1990; van Ingen Schenau & Cavanagh, 1990). Moreover, since gross efficiency does not separate mechanical from physiological efficiency, a change in the effectiveness of running technique will not necessarily be reflected by this parameter. The reason for this is that if an athlete improves his running technique by minimizing mechanical energy losses, the reduced losses at a defined running speed would also result in a reduction of both total mechanical work and metabolic energy expenditure and, thus, their relationship would not change much. Further approaches have been pursued less frequently. In a study of Enomoto, Ae and Okada (1997) the relation between the translational energy of the CG and the total mechanical power was determined to provide a useful index for the effectiveness of the running technique. In several studies mechanical energy losses and energy conservation were analyzed but were not related to total mechanical power in computing an index of effectiveness.
The present study aims at the assessment of the effectiveness of running movements by a combination of approaches. For this purpose "inefficient mechanical work" in the vertical and lateral directions was determined as well as "conservation of mechanical energy" by inter- and intrasegmental energy transfer. These parameters were related to total mechanical work (or power, respectively), to physiological indicators of energy expenditure and to the state of physical training.

METHODS: Ten untrained physical education students and 10 highly-trained runners (specialists) ran 2000m 3-5 times on a 200m indoor track. Before and after each 2000m-run their heart rate and blood lactate were recorded. In 4 subjects wearing a portable spirometer the O_2 consumption and respiratory quotient were determined. The runners were filmed by 2 high-speed cameras (LOCAM) (150 frames/sec). Three dimensional coordinates of 21 points defining a 15 segment

HANAVAN model were constructed using the DLT technique. The data were smoothed by using a low pass filter with a cut-off frequency of 15 Hz. To determine the differences between students and specialists we computed a one-way analysis of variance (ANOVA) with running velocity as covariate. Proceeding from the changes of the translational (ΔE_{trans}), rotational (ΔE_{rot}) and potential energy (ΔE_{pot}) of the 15 body segments, we calculated the mechanical power (P) in x-, y- and z-direction during the support phase (T=support time):

$$P_x = \frac{\left(\sum_i^{15}\sum_t^{T}\left|\Delta E_{transx_{it}}\right|\right)}{T};\; P_y = \frac{\left(\sum_i^{15}\sum_t^{T}\left|\Delta E_{transy_{it}}\right|\right)}{T};\; P_z = \frac{\left(\sum_i^{15}\sum_t^{T}\left|\Delta E_{transz_{it}}\right| - \Delta E_{pot_{it}}\right)}{T}$$

The total mechanical power ($Ptot$) was computed by the summation of the rotatory power ($Prot$) and the power in the x-, y- and z-directions:

$$P_{rot} = \frac{\left(\sum_i^{15}\sum_t^{T}\left|\Delta E_{rotx_{it}}\right| + \left|\Delta E_{roty_{it}}\right| + \left|\Delta E_{rotz_{it}}\right|\right)}{T},\; P_{tot} = P_x + P_y + P_z + P_{rot}$$

The translational power of the CG in the running direction ($PCGx$ "effective mechanical power") was calculated from the translational energy of the CG in the x-direction ($\Delta ECGtransx$):

$$P_{CGx} = \frac{\left(\sum_i^{15}\sum_t^{T}\left|\Delta E_{CGtransx_{it}}\right|\right)}{T}$$

The power of the segmental energy transfer ($P_{transfer}$) was determined using the method of Winter (1979). To describe the effectiveness of the running technique the following effectiveness parameters were calculated:

$$EFsegx = \frac{Px}{Ptot};\; EFsegy = \frac{Py}{Ptot};\; EFsegz = \frac{Pz}{Ptot};\; EF_{CGx} = \frac{Pkspx}{Ptot};\; EF_{transfer} = \frac{P_{transfer}}{Ptot}$$

RESULTS:

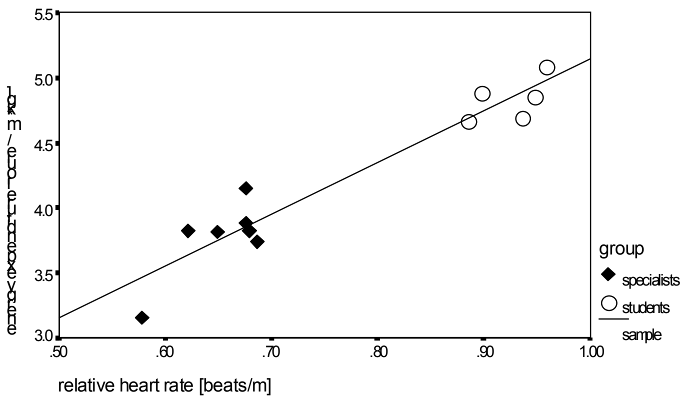

Figure 5 Relationship between heart rate and energy expenditure in 4 subjects

Table 1 Means and standard deviations (SD) of the physiological parameters running speed, training volume, comparison of students and specialists

Parameter	Mean ±SD Students	Specialists	ANOVA
heart rate (beats/min)	179.0 ±12.0	169.5 ±7.6	*
Lactate (mmol/l)	5.6 ±2.9	3.4 ±1.3	**
running speed over 2000m (m/sec)	3.7 ±0.5	4.6 ±0.4	**
weekly training volume (km)	18.2 ±12.7	98.0 ±30.5	**

Table 2 Means ± SD and group differences of the effectiveness parameters

Symbol	Side of support	mean ± SD students	specialists	ANOVA
EFsegx	right left	0.79±0.03 0.76±0.03	0.80±0.02 0.79±0.02	n.s. n.s.
EFsegy	right left	0.021±0.004 0.021±0.005	0.016±0.003 0.015±0.003	* *
EFsegz	right left	0.15±0.02 0.17±0.03	0.13±0.01 0.13±0.01	* *
EFCGx	right left	0.45±0.07 0.45±0.06	0.44±0.04 0.49±0.06	n.s n.s
$EF_{transfer}$	right left	0.46±0.05 0.46±0.04	0.54±0.03 0.53±0.04	** *

Table 3 Correlation between effectiveness and physiological parameters

symbol	side of supp.	heart rate [beats/m]	lactate [mmol/m]	Training Volume
Efsegy	right left	r = 0.54 * r = 0.51 *	r = 0.36 n.s. r = 0.31 n.s.	r =-0.58 ** r = -0.56 *
Efsegz	right left	r = 0.36 n.s. r = 0.46 *	r = 0.19 n.s. r = 0.25 n.s.	r = -0.44 n.s. r =-0.64 **
$Ef_{transfer}$	right left	r = - 0.57 ** r = - 0.43 *	r = - 0.54 * r = - 0.40 n.s.	r = 0.76** r = 0.65**

DISCUSSION: The main components of mechanical power, derived in this study from kinematic data, have shown that, compared to non-specialized students, specialists in middle-/long-distance running perform less mechanical work in the lateral and vertical directions in relation to total mechanical power. Moreover, the specialists are characterized by a higher inter- and intrasegmental energy transfer than the students. These results correspond to observations of a higher energy transfer and less vertical displacement of CG in economical than in less economical runners (Williams & Cavanagh, 1987). The plausible assumption that the specialists may also transform energy in the running direction more economically than the students is supported in the present study only by a (nonsignificant) trend found for the relevant effectiveness parameters *EFsegx* and *EFCGx*. This may be due to the particular method used to determine the effective work in the running direction which was calculated by summing up positive and negative segmental work. With this approach, a higher "braking work" in running will necessarily result in a larger quotient by which effectiveness is described. The correlations between relative heart rate and the effectiveness parameter *EFsegy* and $EF_{Transfer}$ indicate a positive relationship between running economy and effectiveness. This conclusion is not unequivocal, because cardiovascular adaptation to exercise in the course of training will lead to lower heart rates at a given rate of metabolic activity. However, the close relationship between heart rate and energy expenditure per unit running distance shown for the two groups in Figure 1 suggests that, indeed, the locomotion of the trained specialists is energetically more economical. The significant correlations between the effectiveness parameters (*EFsegy, EFsegz,* $EF_{transfer}$) and training volume indicate that running training involves a self-optimization process resulting in higher mechanical effectiveness of the running technique. This conclusion is in line with the results of a learning experiment by Sparrow and Irizzary (1987) in which training for a novel gross motor task improves economy due to an improvement in segmental energy transfer.

CONCLUSION: The evaluation of indices of effectiveness in the described way is a useful method to monitor the progress of training, especially because its results are quite robust with respect to the influences of running speed and data filtering.

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