RUNNING ECONOMY IS A MULTIFACTORIAL PHENOMENON

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The purpose of this review was to describe economy of human locomotion, especially in running. Several factors such as age, sex, air resistance, body temperature, body weight, maximal aerobic capacity, muscle fibre distribution, vertical oscillation of the body, ground reaction forces and their directions, tendomuscular structure, training status, and fatigue have been demonstrated to affect running economy (RE). Although there exist interindividual differences in RE, training, especially strength and power training, improves RE to a certain degree. On the contrary, RE decreases in fatiguing conditions, but negative influences on RE can be minimized by optimal training.

KEY WORDS: running, training, fatigue.

INTRODUCTION: Muscular exercises seldom involve pure forms of isolated isometric, concentric or eccentric actions. This is because the body segments are periodically subjected to impact forces, as in running or jumping, or because some external force such as gravity lengthens the muscle. In most human motions, skeletal muscles act through a stretch-shortening cycle (SSC) (Norman and Komi, 1979), which may enhance the mechanical outputs of the muscle and, therefore, the logical consequence should be that work efficiency is also enhanced.

Marey and Demeny wrote already in 1885 as follows: "If we perform two successive vertical jumps exerting each time our maximal effort, it always happens that the second jump is higher than the first one. The storage of work in the tense muscles gives to it, since beginning of the second jump, a very high elastic force which on the contrary was developed only gradually by the muscle during the first jump". Over a hundred years later their observations have been used to evaluate the contribution of elastic energy in human locomotion (Asmussen and Bonde-Petersen 1974; Cavagna 1977; Kaneko et al 1984).

To start the discussion on efficient and economical movement of SSC actions, various definitions need to be addressed briefly. Mechanical efficiency (ME) incorporates two processes, phosphorylation coupling and contraction coupling, in converting energy from one form to another (Whipp and Wasserman, 1969). In an isolated situation, muscular efficiency is about 28%. Mechanical work is missing from the determination of the term economy, but submaximal oxygen uptake per unit body mass required to perform a certain task is widely accepted as the physiological criterion for efficient movement. The purpose of this short review was to describe running economy (RE) and factors affecting it. In particular, the roles of training and fatigue in RE were emphasized.

RUNNING ECONOMY: In running, values of ME have varied enormously (from 19 to 80%) depending on the methods used to measure and calculate mechanical work and energy expenditure (e.g. Cavagna et al. 1965; Margaria 1968; Asmussen & Bonde-Petersen 1974; Cavagna & Kaneko 1977; Ito et al 1983). Various factors such as age (e.g. Daniels et al. 1978), sex (e.g. Bransford & Howley 1977), air resistance (e.g. Costill & Fox 1969), body temperature (e.g. Rowell et al. 1969), body weight (e.g. Cureton et al. 1978), maximal aerobic power (e.g. Mayhew 1977), and muscle fibre distribution (e.g. Bosco et al. 1987; Kyröläinen et al. 2003) have been found to affect running efficiency / economy.

It has also been suggested that biomechanical factors may account for a substantial portion of variations in RE. As compared to a less successful runner, a faster endurance runner is characterized by less vertical oscillation (Gregor & Kirkendall 1978), longer strides (Hoshikawa et al. 1971; Cavanagh & Williams 1982), less change in velocity during ground contact (Kaneko et al. 1985), and lower first peak in the vertical component of the ground reaction force associated with a tendency towards smaller anteroposterior peak forces (Williams & Cavanagh 1987). It has also been shown that less economical runners exhibit greater total and net vertical impulses, while other parameters of ground reaction forces are not associated with RE (Heise & Martin 2001). Furthermore, there are runner, shoe and surface interactions. For example, Roy and Stefanyshyn (2006) found that higher shoe midsole longitudinal bending stiffness was associated with improved RE.

Interindividual variations demonstrate that subjects trained in endurance running are more economical than their untrained counterparts (Bransford & Howley 1977), while intraindividual variation in RE reportedly varies between 2 and 11% (Morgan et al. 1989). Figure 1 shows RE among middle-distance runners at different running speeds. It shows nicely that a runner who is economical at a given running speed will usually be economical at other speeds as well (Williams 1990; Kyröläinen et al. 2003), and the interactions between mechanical and metabolic variables appear to be very complex (Mayhew 1977; Lake & Cavanagh 1996; Kyröläinen et al. 2003). However, a puzzling question is: what are the factors that explain differences in running economy?

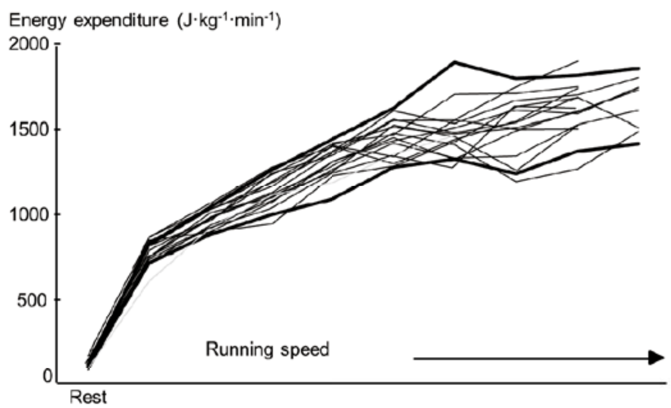

Figure 1: Individual (n=17 middle-distance runners) energy expenditure curves as a function of running speed from 3.5 up to 7.0m·s^{-1}.

In recent years, studies attempting to explain differences in RE have concentrated on muscle mechanics. Arampatzis et al. (2006) found that the most economical runners showed higher contractile strength and higher normalized tendon stiffness (ratio between tendon force and strain) in the triceps surae muscle-tendon unit and a higher compliance of the quadriceps tendon and aponeurosis at low tendon forces. Kunimasa et al. (2014) and Sano et al. (2015) compared Kenyan and Japanese runners. They observed that elite Kenyan runners had longer Achilles tendons and tendon moment arms, which may result in the reduction of Achilles tendon strain and medial gastrocnemius (MG) muscle activation, and therefore lower oxygen consumption requirements. As a consequence, this may allow MG fascicles to work more isometrically during the contact phase of running. Among Kenyan distance runners, Mooses et al. (2015) also found that Achilles moment arm length was associated with better RE. In addition, they observed that longer leg length, but not RE, was related to better running performance, suggesting that RE can be compensated by other factors.

TRAINING AND ECONOMY: It is quite well documented that strength training not only improves RE but also muscle power and performance (Beattie et al. 2014). For example, Millet et al. (2002) studied triathletes who trained for 14 weeks. They found that the group who also did two heavy weight training sessions in a week improved their RE, which was not the case in the endurance-only group. In the study of Storen et al. (2008), 8 well-trained runners performed half-squats (4x4 repetitions) 3 times per week for 8 weeks, and their 7 counterparts trained only endurance. The intervention group improved RE by 5.0%, maximal force by 33.2%, rate of force production by 26.0%, and time to exhaustion by 21.3%.

Albracht and Arampatzis (2013) studied the effects of 14-weeks of strength training of the plantarflexor muscles on tendon-aponeurosis stiffness and contractile strength, and their associations with RE. They observed enhanced RE after increasing triceps surae tendon stiffness and contractile strength, which may indicate that force generation during running became more economical within the lower extremities due to higher energy storage and release in the series elastic elements of the triceps surae.

FATIGUE AND ECONOMY: There are several factors that may reduce RE in fatiguing conditions. 1) Metabolic factors, including changes in energy sources during running that has been shown to cause a reduction of 0.07 in respiratory exchange ratio and a shift to fatty acid oxidation (Kyröläinen et al. 2000). In addition, body temperature regulation requires energy (Saltin et al. 1966), and microstructural muscle damage consisting of increased cytokines may decrease RE (Kyröläinen et al. 2000). 2) Mechanical factors refer to changes in running technique such as an increase in stride frequency, a decrease in stride length (Morin et al. 2011), and possible changes in contact times, vertical displacements of the body, and changes in arm movements. 3) Neuromuscular factors have also been shown to change during prolonged running. Maximal activation of the leg extensor muscles decreases (Avela et al. 1999) but in submaximal running EMG activity increases (Komi et al. 1986) due to the recruitment of more motor units and an increase of their firing frequency.

CONCLUSION: RE is a multifactorial phenomenon, and it cannot solely be explained by mechanical factors. The complex links between utilization of different energy sources, thermoregulation, body composition, tendomuscular structure, muscle activation and damage should be studied. The good news is, however, that optimal training makes it possible to improve RE.

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