Factors Related to Top Running Speed and Economy

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Key words
- running economy
- distance running
- ground reaction force
- stride length
- ground contact time

Abstract

The main purpose of the present study was to investigate the relationships between running mechanics, top running speed and economy in young endurance athletes. Twenty five endurance athletes (age 19.8 ± 1.1 years, stature 1.82 ± 0.07 m and body mass 69.4 ± 7.5 kg) performed two separate tests on an indoor track. The first test was 8 × 30 m with increasing speed, and the second test was incremental 5 – 6 × 1000 m. In the first test, ground reaction forces and stride characteristics were measured from each running speed. In the second test, running economy at the speed of $3.89\,m \cdot s^{-1}$ and maximal oxygen uptake were determined. Ground contact time was the only factor which correlated significantly with both running economy ($r = 0.49$, $p < 0.05$) and maximal running speed ($r = -0.52$, $p < 0.01$). Furthermore, maximal running speed was correlated significantly with the mass-specific horizontal force ($r = 0.56$, $p < 0.01$) but not with the vertical effective force. It is concluded that the short contact times required in economical and high speed running suggests that fast force production is important for both economical running and high top running speed in distance runners.

Introduction

Running economy is strongly related to distance running performance [4,19], and it is typically determined by measuring the steady-state oxygen consumption at the submaximal running speed. Taking body mass into consideration, runners with good running economy use less energy and therefore less oxygen than runners with poor running economy at the same speed. Researchers have reported a 20 – 30% range in the oxygen consumption for a given submaximal running speed among trained distance runners [4,6,18]. Interindividual variability in running economy has been explained by various physiological, biomechanical, environmental, anthropometrical and psychological factors. Biomechanists have identified that running economy is affected by the net vertical impulse of the ground reaction force [9], stride length [3], change in speed during ground contact phase [11] and vertical stiffness of a leg spring [5,9].

Running speed is the product of stride rate and stride length. Although both stride rate and stride length are increased with increasing running speed, stride length is responsible for increasing speed up to 90% of an individual maximum speed and, thereafter, the speed is only increased by increasing stride rate [15,16,23]. Cavanagh and Williams [3] found the most economical stride length of a group of runners was close to that which was freely chosen. Ground contact phase is the only phase during a running cycle in which a runner can produce force and influence stride length and running speed. Functional and mechanical requirements during stance are reflected in the characteristics of the ground reaction force. It has been shown that vertical and horizontal components of ground reaction forces increase with increasing running speed [14,16,23]. Weyand et al. [23] concluded that runners reach faster top speeds by applying greater support forces to the ground not by more rapid leg movements. The critical point in maximal sprint running is the change in running speed during the ground contact phase. The horizontal breaking force and braking time as well as the horizontal distance between the first contact point and the center of gravity of the body at touchdown should be very small to avoid loss of speed during the braking phase of ground contact [17].

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The amount of energy used to run a constant distance is nearly the same whether it is run at top speed or at leisure pace. The results of Kram and Taylor [13] suggest that, primarily, the cost of supporting the body weight and the time course generating this force determines the cost of running. Therefore, a long ground contact phase and great deceleration of horizontal speed during a braking phase of the ground contact could be considered wasteful in terms of the metabolic energy requirements. A successful endurance runner is characterized by less vertical oscillation [7], longer strides [3], shorter ground contact times [21], less change in speed during the ground contact [11], and lower first peak in the vertical component of the ground reaction force, associated with a tendency to have smaller anteroposterior peak forces [25]. In a well controlled study, Heise and Martin [9] showed that less economical runners exhibited greater total and net vertical impulse, indicating wasteful vertical motion.

It is a well known fact that elite sprint runners have a higher top running speed and a lower running economy than elite distance runners. Although there is a discrepancy between the high neuromuscular capacity to produce force and running economy, some previous studies have shown that the explosive type strength training can be used to improve both maximal power output and running economy [10,20]. Therefore, the main purpose of the present study was to investigate the factors of running stride, which were related to both top running speed and running economy in young endurance athletes.

Methods

Subjects

Twenty-five young male endurance athletes (ten distance runners, eight orienteers and seven triathletes) volunteered as subjects for the present study. All the athletes belonged to the national junior team and their mean ± SD age, height and body mass were: 19.8 ± 1.1 years, 1.82 ± 0.07 m and 69.4 ± 7.5 kg, respectively. All the subjects were fully informed of the procedures and possible risks of the experiments, and written informed consent was obtained from each subject. The informed consent was in accordance with the guidelines of the Ethical Committee of the University of Jyväskylä. The tests of the present study were part of the athletes normal exercise testing and they complied with current Finnish laws regarding the testing of human subjects.

Procedure and measurements

In order to measure ground reaction forces and stride characteristics at different running speeds and determine maximal sprinting speed, running economy, distance running performance and maximal oxygen uptake, the athletes ran two separate running tests on a 200-m indoor track. The first test was 8 × 30 m with increasing speed, and the second test was an incremental 5–6 × 1000 m.

In the first test (8 × 30 m), the athletes were able to accelerate 50 m to ensure a normal and steady running gait throughout the 30-m measurement section. The speed of the first run was $5.0\,m \cdot s^{-1}$ and, thereafter, the speed was increased by $0.40\,m \cdot s^{-1}$ after each run until the sixth run ($7.0\,m \cdot s^{-1}$). The running speed was regulated by small lights placed on the next lane at intervals of 4.0 m (Naakka Ltd., Lappeenranta, Finland). The athletes were instructed to adjust their speed to coincide with the lights, which were switched on and off along the track. The athletes were asked to run the last two runs at maximal speed. Each running bout was separated by a two-minute recovery period during which the runners returned to the start of the sprint course. In order to measure running speed, stride rate and stride length, a photocell contact mat [22] and two photocell gates were placed on the sprint course (Ivar Ltd., Tallin, Estonia). A special 9-m long force platform system was placed in the middle of the 30-m measurement section. The system consisted of five two dimensional (2D) and three 3D force platforms (0.9 × 1.0 m each, TR Test Ltd., Jyväskylä, Finland, natural frequency in the vertical direction 170 Hz) and one Kistler 3D force platform (0.9 × 0.9 m, 400 Hz, Honeycomb, Kistler, Switzerland) connected in series and covered with a tartan mat. Each force platform registered both vertical and horizontal components of the ground reaction forces. Vertical and horizontal ground reaction forces were recorded by a microcomputer using an AT Codas A/D converter card (Dataq Instruments, Inc., Akron, OH, USA) with a sampling frequency of 1000 Hz.

The incremental 5–6 × 1000-m test was performed after 15 min recovery from the first test. The initial speed was $2.78\,m \cdot s^{-1}$ for the orienteers and triathletes and $3.33\,m \cdot s^{-1}$ for the distance runners. Thereafter, the speed was 3.89, 4.44, 5.00, and $5.56\,m \cdot s^{-1}$. The running speed was regulated by small lights embedded on the inside of the 200-m indoor track at intervals of 4.0 m (Naakka Ltd.). The athletes were instructed to adjust their speed to coincide with the lights, which were turned on and off inside the track. The athletes were asked to run the last 1000 m at maximal effort. The athletes performed five or six runs depending on their maximal aerobic capacity. Oxygen consumption and heart rate (Oxycon Mobile, Viasys Healthcare GmbH, Hoechberg, Germany) were measured continuously during the whole test. Running economy was measured as steady-state oxygen uptake of submaximal running at the speed of $3.89\,m \cdot s^{-1}$, and maximal oxygen uptake ($\dot{V}O_{2max}$) was defined as the highest oxygen consumption during the test over a 60-second period. Running economy and maximal oxygen uptake were expressed as $ml \cdot kg^{-0.75} \cdot min^{-1}$, since submaximal $\dot{V}O_2$ and $\dot{V}O_{2max}$ measures during running may be better related to the 0.75 power of body mass than $[body \cdot mass]^{-1}$ [1].

Data analysis

Three to five contact phases of each subject at all running speeds were selected for analysis. The horizontal force-time curve was used to separate the ground reaction forces into the braking and propulsion phases [16]. The integrals of both force-time curves were calculated and divided by the respective time period to obtain the average force for the whole contact phase and for horizontal braking and propulsion phases separately. The effective force (F_{yeff}) which exceeds the body mass was determined from $(F_y - F_{BW}) \cdot F_{BW}^{-1}$, where F_{BW} = body weight.

Effective impulse values were determined from the effective force applied to the running surface and ground contact times: $F_yI_{eff} = F_{yeff} \cdot CT$, where CT = ground contact time. CT was determined from the time the applied vertical force exceeded 0 N on the force platform. Horizontal impulses (F_xI) were calculated as absolute impulses because horizontal force displays negative values during breaking phase and positive values during propulsion phase: $F_xI = (F_x \cdot F_{BW}^{-1}) \cdot CT$.

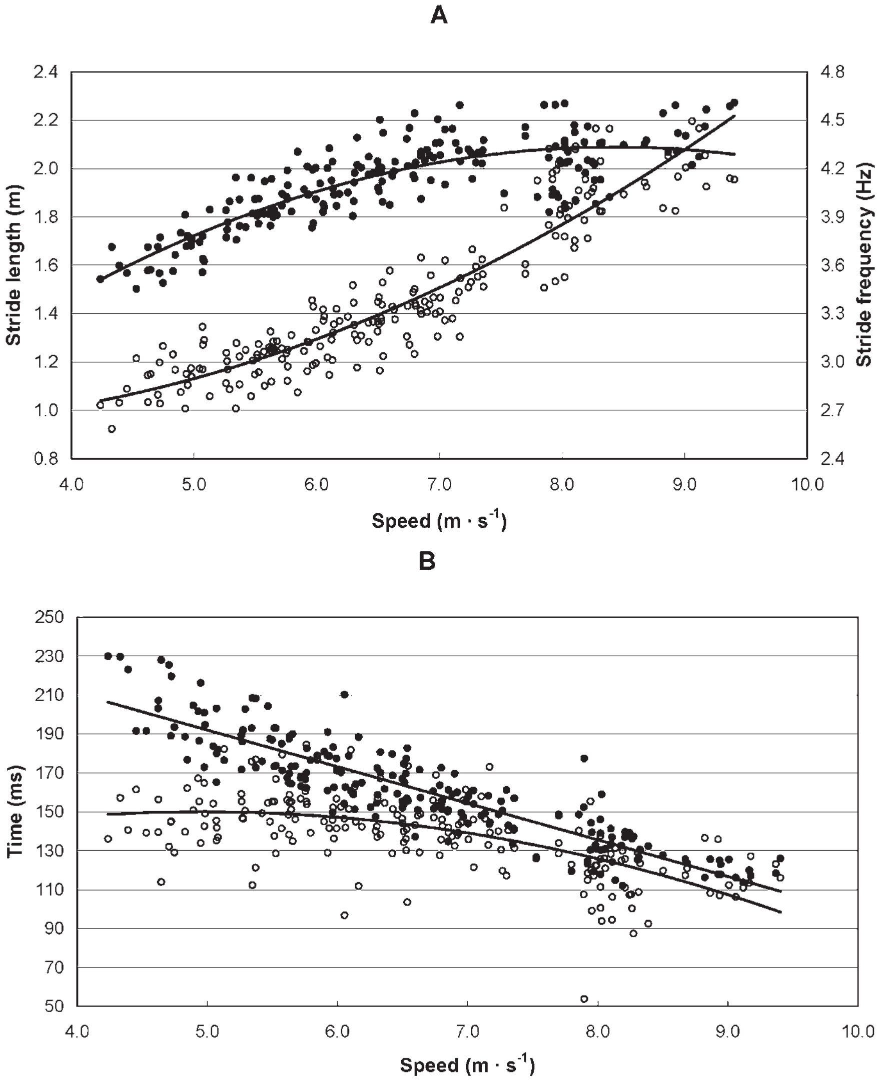

Fig. 1 A and **B** Running mechanics as a function of speed for the data of 25 endurance athletes with eight different speeds. Each dot represents the average value of a certain speed of an athlete. Linear or second order polynomial trend line is also added in the figures. **A** Increase in stride length (dots) and stride frequency (open circles) with increasing speed. **B** Decrease in ground contact time (dots) and flight time (open circles) with increasing speed.

Statistics

The relationship between running speed, top running speed, running economy and ground reaction force characteristics were investigated using a standard Pearson product moment correlation and linear regression analyses. Values are expressed as mean ± standard deviation. All the statistical analyses were undertaken using SPSSWIN 13.0 (SPSS, Inc., Chicago, IL, USA).

Results

Running economy and $\dot{V}O_{2max}$

Although the subjects were all endurance athletes and belonged to the national junior team, their $\dot{V}O_{2max}$ and maximal 1000-m speed was quite heterogeneous ranging from 152 to 240 ml·kg$^{-0.75}$·min^{-1} (184 ± 18 ml·kg$^{-0.75}$·min^{-1} or 63.9 ± 5.7 ml·kg^{-1}·min^{-1}) and from 4.31 to 6.27 m·s^{-1} (5.32 ± 0.55 m·s^{-1}), respectively. Running economy or oxygen uptake at the speed of 3.89 m·s^{-1} ranged from 121 to 161 ml·kg$^{-0.75}$·min^{-1} (144 ± 10 ml·kg$^{-0.75}$·min^{-1} or 49.9 ± 3.3 ml·kg^{-1}·min^{-1}), which were typical of those which have been reported previously for similar speeds [9,21]. The difference between the most and least economical runners showed that the athletes were much more homogeneous in terms of running economy than they were in $\dot{V}O_{2max}$.

Running mechanics as a function of speed

In pooled data across the speed range, speed increases were achieved by increasing both stride lengths and stride frequencies at the speeds below 7 m·s^{-1}, and at the speeds above 7 m·s^{-1}, stride frequency was solely responsible for speed increase (**Fig. 1 A**). The increases in stride frequencies resulted from the reductions in ground contact time at speeds below 6 m·s^{-1}, although stride frequency depends on both contact time and flight time (**Fig. 1 B**). As subjects approach their top speed, both contact time and flight time decreased. These flight time reductions coincided with the decreases in effective vertical impulse and horizontal impulse (**Fig. 1 C, D**). In pooled data, the increase in stride length was related to the increase in effective vertical force ($r = 0.58$, $p < 0.001$) and horizontal propulsion force ($r = 0.73$, $p < 0.001$, **Fig. 2**) but not with the vertical effective impulse or horizontal impulse.

Maximal running speed

In the present athletes, maximal 30-m running speed ranged from 7.70 to 9.40 m·s^{-1} (8.39 ± 0.45 m·s^{-1}). Maximal running speed of the athletes was significantly correlated with the ground contact times ($r = -0.52$, $p < 0.01$, **Fig. 3 A**) and braking phase time ($r = -0.64$, $p < 0.001$) but not with the propulsion phase time. The mass-specific vertical force was not related to the maximal running speed, but a significant correlation was ob-

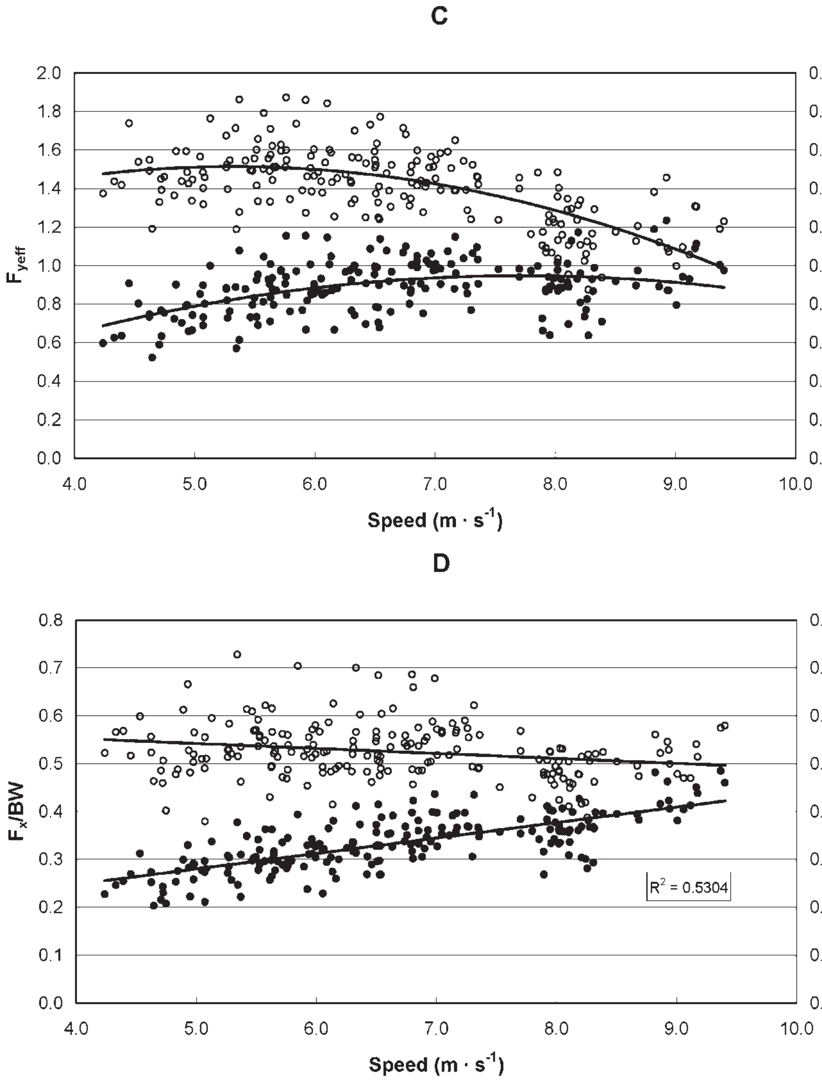

Fig. 1 C and **D** Running mechanics as a function of speed for the data of 25 endurance athletes with eight different speeds. Each dot represents the average value of a certain speed of an athlete. Linear or second order polynomial trend line is also added in the figures. **C** Increase in vertical effective force (dots) and decrease in vertical effective impulse (open circles) with increasing speed. **D** Increase in mass-specific horizontal force (dots) and horizontal impulse (open circles) with increasing running speed.

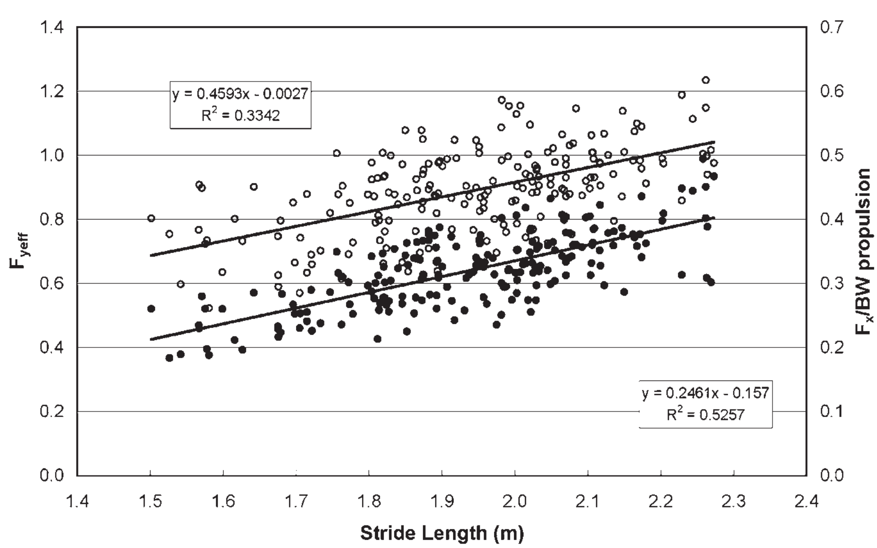

Fig. 2 Vertical effective force (open circles) and mass-specific horizontal force (dots) during a propulsion phase as a function of stride length.

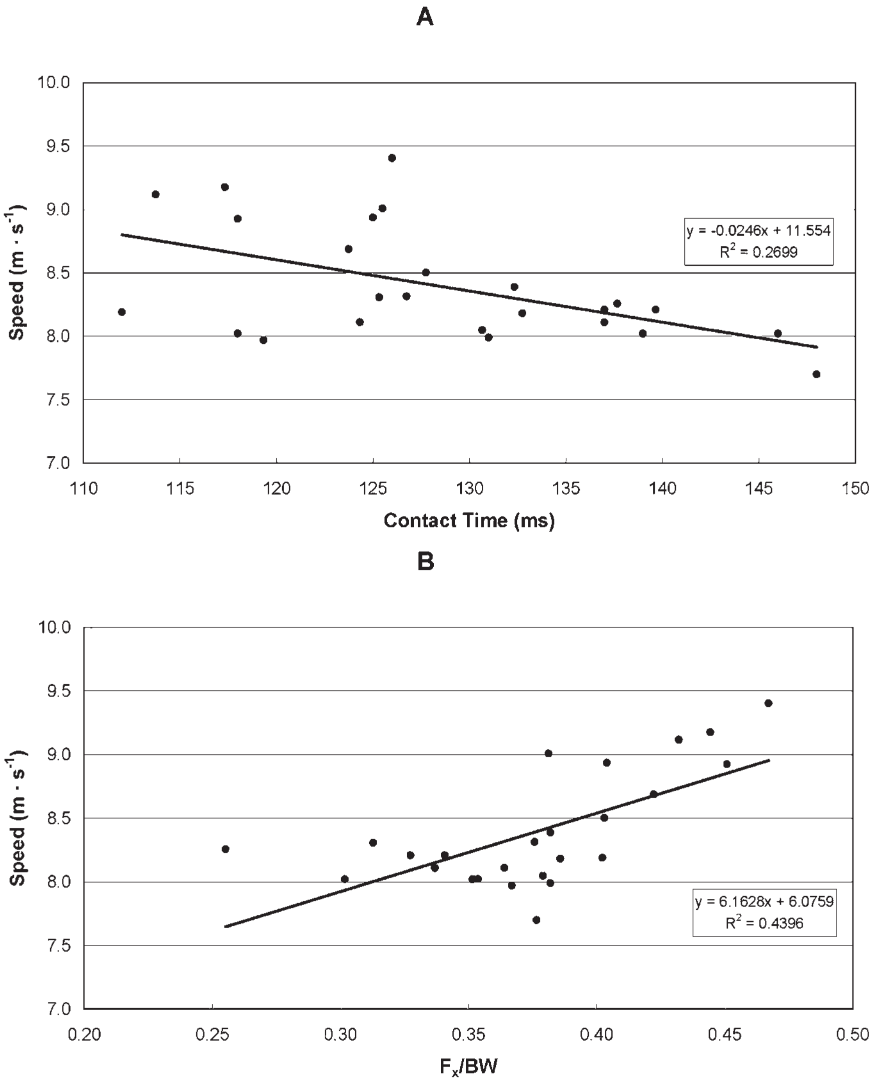

Fig. 3 A and **B** Ground contact time (**A**) and mass-specific horizontal force during a propulsion phase (**B**) as a function of maximal running speed for 25 endurance athletes.

Table 1 Ground contact time, vertical effective impulse and relative stride length (stride length · $stature^{-1}$) of the two most economical runners (RE121 ml · $kg^{-0.75}$ · min^{-1} and RE123 ml · $kg^{-0.75}$ · min^{-1}), the two most uneconomical runners (RE158 · $kg^{-0.75}$ · min^{-1} and RE161 ml · $kg^{-0.75}$ · min^{-1}) and average value of the whole group. The ground reaction force and stride characteristics are average values from the velocity of 5.8 m · s^{-1}

	RE121	RE123	Mean ± SD	RE158	RE161
CT (ms)	165	150	175 ± 13	190	170
F_yI_{eff} (s)	0.144	0.151	0.154 ± 0.014	0.151	0.160
Rel SL	1.03	1.04	1.03 ± 0.05	1.03	1.07

CT: ground contact time; F_yI_{eff}: vertical effective impulse; Rel SL: relative stride length; RE: running economy

served between the maximal running speed and the mass-specific horizontal forces of the whole ground contact ($r = 0.56$, $p < 0.01$) and propulsion phase ($r = 0.66$, $p < 0.001$, **Fig. 3 B**) but not braking phase.

Running economy

In order to investigate the relationships between running economy and ground reaction force and stride characteristics, the values at the running speeds of 5.4, 5.8, 6.2, and 6.6 m · s^{-1} were used in the analyses. No correlation was observed between ground reaction force characteristics and running economy. The only significant correlations were observed between running economy and ground contact time at the running speeds of 5.8 m · s^{-1} ($r = 0.49$, $p < 0.05$), 6.2 m · s^{-1} ($r = 0.44$, $p < 0.05$) and 6.6 m · s^{-1} ($r = 0.41$, $p < 0.05$). Although there were only few significant correlations between running economy and ground reaction force and stride characteristics, biomechanical factors might explain individual differences in running economy as shown in **Table 1**.

Discussion

The present study was designed to investigate the relationships between force production and running economy and running speed in endurance athletes. Previous studies have shown a discrepancy between running economy and top running speed,

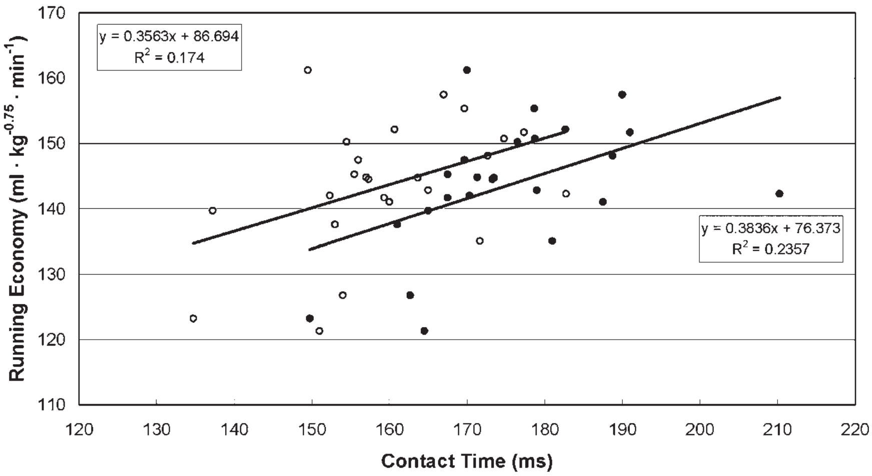

Fig. 4 The relationships between running economy or oxygen uptake (3.89 $m \cdot s^{-1}$) and ground contact time at the speeds of 5.8 $m \cdot s^{-1}$ (dots) and 6.6 $m \cdot s^{-1}$ (open circles).

since both can be improved by strength training [20] but the fastest runners apply greater support forces to the ground [23] and less economical runners exhibit greater ground reaction impulses [9]. In the present study, ground reaction force characteristics were related to running speed but not to running economy. The ground contact time was the only stride variable, which was related to both running speed and running economy.

It is well known that ground contact time decreases linearly with increasing running speed [15] and this was also observed in the present study (**Fig. 1 B**). The relationship between running economy and short contact times has also been observed in a previous study [21]. Furthermore, Williams [24] has found that during submaximal running, ground contact times differ between a rearfoot and a midfoot striker. Short contact time seems to be beneficial for both running economy and maximal running speed. This seems to be logical since the critical point in maximal sprint running and economical running is the speed lost during the breaking phase [17]. The horizontal braking force and braking time as well as the horizontal distance between the first contact point and the center of gravity of the body at touchdown should be very small to avoid loss of speed during the braking phase of ground contact. Kyröläinen et al. [14] suggested that increasing the pre-landing and braking activity of the leg extensor muscles might prevent unnecessary yielding of the runner during the braking phase, helping them tolerate higher impact loads. A short and rapid stretch with a short coupling time and a high force at the end of pre-stretch creates a good precondition for utilizing elasticity [2,12]. Pre-activity increases the sensitivity of the muscle spindle via enhanced alpha-gamma coactivation potentiating stretch reflexes, and enhancing musculo-tendon stiffness, with a resulting improvement in running economy.

In a well controlled study, Heise and Martin [9] observed that less economical runners exhibited greater total and net vertical impulse, indicating wasteful vertical motion. The influence of the total vertical impulse was 38% of the interindividual variability in running economy. In the present study, no significant correlation was observed between any ground reaction force characteristics and running economy. One reason for the difference in the results might be that in the study of the Heise and Martin [9] the ground reaction forces were measured from the same running speed (3.35 $m \cdot s^{-1}$) as the running economy. In the present study, we assumed that a runner who is economical at a given running speed will be economical at other speeds as well and therefore ground reaction forces were measured from the running speeds which were close to the athletes' speed during a track running competition. A number of physiological and biomechanical factors appear to influence running economy in endurance athletes and therefore the interactions between mechanical and metabolic variables appear to be very complex [14, 25]. This is one reason why in some studies a relationship exists between ground reaction force characteristics and running economy [9] and in some other studies not (present study, [14]). Based on the findings of the previous studies, we could hypothesize that short ground contact time [21], low vertical effective impulse [9] and optimal or self-selected stride length [3] at a given speed are associated with high running economy. Although we did observe a significant correlation only between contact time and running economy, vertical impulse and stride length might also explain individual differences in running economy. Excellent running economy of the two most economical runners in the present study can be explained, at least partly, by short ground contact times (**Table 1**). Furthermore, the high running economy of the RE121 (**Table 1**) could also be explained by the low vertical effective force. On the other hand, the same biomechanical factor did not explain the poor running economy of the two least economical runners in the present study (**Table 1**). One possible reason for the poor running economy for the RE158 (**Table 1**) is long ground contact times, whereas high vertical effective impulse and long relative stride length might explain, at least partly, why the RE161 (**Table 1**) used more oxygen than the other runners in the present study. These individual examples showed the complexity of the running economy, and that none single biomechanical factor can fully explain the differences in running economy between the individual runners.

Stride length, stride frequency, ground contact time and flight time as a function of running speed in the present study (**Fig. 1 A, B**) are well in line with previous findings [15,16,23]. The results of the present study also showed that the increase in stride length resulted from increasing both vertical and horizontal ground reaction forces (**Fig. 2**). These relationships seem obvious, since ground contact is the only phase during the running cycle in which a runner can produce force and influence stride length and running speed. Vertical effective force increased with the increasing speed until the speed of 7 $m \cdot s^{-1}$, thereafter the speed was increased without further increase in vertical effective force (**Fig. 1 C**) and no correlation was observed between the vertical effective force and maximal running speed in present athletes. This is contradictory to the results of Weyand et al. [23]. They concluded that runners reach faster top speeds by applying greater vertical support forces to the ground. In the present study, horizontal force increased linearly with the running speed (**Fig. 1 D**), and a significant relationship was observed between maximal running speed and horizontal force (**Fig. 3 B**). The results of the present study suggest that maximal running speed is more dependent on horizontal than vertical force. This seems to be logical since one can not increase horizontal speed by increasing vertical force, but acceleration and deceleration of running speed is produced mainly by changing horizontal force.

In conclusion, only ground contact times exhibited statistically significant correlations with both running economy and maximal running speed. This suggests that the short braking phase and use of elastic energy are important factors both in economical and high speed running in the group of young well-trained endurance athletes. Although any other biomechanical factors did not correlate with running economy, there are numerous biomechanical factors which could be used to partially explain differences in running economy between two runners. Another important finding of the present study was that horizontal ground reaction force was linearly increased with running speed and was correlated with the maximal running speed. This suggests that the horizontal component of ground reaction force is more important in attaining high top running speed in distance runners than the vertical component of it, since similar linear relationships were not observed between vertical effective force and running speed, and no significant correlation was observed between vertical force and maximal running speed.

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