Muscle fatigue in middle-distance running

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ABSTRACT

This study investigated fatigue-induced changes in neuromuscular and stride characteristics during and immediately after a hard middle-distance running effort. Eighteen well-trained male distance runners performed a maximal 20m sprint test and maximal voluntary contractions (MVC) on a leg press machine before and immediately after a 5000m time trial. In all the tests the EMG of five lower limb muscles was measured. The results showed that muscle fatigue measured in maximal exercises is not related to the fatigue induced changes during the time trial. The fatigue in the 20m sprint test was related to the maximal 20m pre-test velocity, but the velocity loss during the time trial was inversely related to 5000m performance and training volume. The authors conclude that the fatigue measured at maximal effort both pre- and post-time trial is more related to sprint performance than endurance performance and that the fatigue measured during the time trial is related to endurance performance and factors affecting pacing strategy. The findings support the idea that pacing strategy is regulated in an anticipatory manner by a central governor, which ensures that physiological reserves are maintained. This article was originally published in the International Journal of Sport Medicine under the title "Fatigue during a 5-km running time trial".

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Introduction

Muscle fatigue is a complex phenomenon that can be defined as an inability to maintain a level of force production or as a reduction in the maximum force that a muscle can exert[20]. After exercise involving long-term running, the isometric strength loss is related in a non-linear way to the exercise duration[20]. A decrease in maximal running speed and an increase in ground contact time also occur after long running exercises[2, 17, 21, 31].

Muscle fatigue may arise not only because of peripheral changes at the level of the muscle, but also because the central nervous system fails to drive the motor neurons adequately. It has been suggested that during long-duration exercise central fatigue may develop[7]. Furthermore, metabolic and structural changes[14, 15, 30] may be related to muscle fatigue after long-duration exercise. It has also been suggested that in an exercise such as running, which repetitively evokes the stretch shortening cycle, performance may be impaired partly from alterations in stiffness regulation[2].

A decrease in integrated electromyography (EMG) activity during maximal voluntary contraction and during maximal velocity running has been recorded for lower limb muscles after prolonged runs[3, 19, 21, 31]. The effects of fatigue on EMG activity in submaximal exercises are not as clear as the reduced EMG activity in maximal efforts. NICOL et al.[22] observed that the integrated EMG of the gastrocnemius muscle increased during the push-off phase at submaximal running velocity after the marathon. AVOGADRO et al.[4] and PAAVOLAINEN et al.[31] measured EMG activity of lower limb muscles during a fatiguing running exercise. They did not observe any changes in integrated EMG values at submaximal running velocities. BORRANI et al.[6] observed a progression in the average frequency of the motor unit discharge toward the high frequencies, which coheres with the hypothesis of the progressive recruitment of fast-twitch fibres during the VO_2 slow component.

Self-selected pacing strategy during a time trial plays a key role in a complex regulatory system, in which an integrated neural control regulates running intensity to ensure that any damage to cellular function does not occur[13, 16, 25, 26, 34]. Optimal pacing strategy differs for distances shorter than 800m compared to distances 1500 to 10,000m[27, 37, 38]. In the optimal short-term races (<800m), the highest running velocities are achieved after the acceleration phase, and thereafter the running velocities decreased gradually to the end of the race. In longer duration events, pacing strategy is regulated to ensure that a reserve is maintained, and therefore the highest velocities occur at the end of the race[38]. It has been proposed that the brain uses an “internal clock” to generate knowledge of the distance still to be covered, so that running velocity and metabolic rate can be altered appropriately during the time trial[35]. Therefore analysing the pacing strategy in time trial events may allow insight into the muscle fatigue and related physiological and regulatory processes. In the present study a 5000m time trial was selected, since in 5000m world record runs pacing strategy has been remarkably consistent. Either the first kilometre or the final kilometre is always the fastest while the middle part of the race, from 2 - 4km, has never been faster than either the first or the final kilometre in any world record performance[38].

Most studies have examined muscle fatigue and related neuromuscular alterations by looking at the difference in maximal performance between pre- and post-exercise but little is known about the development of fatigue during the exercise. Therefore the aim of the present study was to compare the changes in EMG activity, force production and running stride characteristics in maximal short-term performance pre- and post-exercise to the respective changes developed during a 5000m running time trial. We hypothesized that the changes in maximal short-term performance (MVC and 20m sprint running) after a fatiguing endurance exercise are not completely related to the respective changes during the self paced endurance exercise.

Materials and Methods

Subjects

Eighteen well-trained male distance runners were recruited to participate in this study. Subjects were included if they were able to complete 10km in under 38 minutes. Each subject signed an informed consent form at the beginning of the study. The study was performed in Cape Town and approved by both the Ethics and Research Committee of the Faculty of Health Sciences, University of Cape Town, South Africa and the Ethics Committee of the University of Jyväskylä, Finland.

Experimental design

The subject runners were required to visit the laboratory on three separate occasions over a ten-day period. They were asked to maintain their regular physical activity pattern for the duration of the study and were requested not to exercise on the morning prior to their testing. On their first visit to the laboratory, the subjects were given the opportunity to become familiar with equipment and testing protocols that would be used during the trial. This familiarisation was performed in an attempt to reduce error associated with subjects performing unaccustomed exercise. The volume of training ($km \cdot week^{-1}$) and racing history during the preceding three months was also obtained from each subject.

On the first testing day, the subjects performed the 5000m time trial and two maximal performance tests before and immediately after the time trial. The maximal performance tests were a 20m maximal sprint with a running start of 15m and maximal voluntary contraction (MVC) with knee extensor muscles.

On their next visit to the laboratory, no more than seven days later, peak treadmill running speed (PTRS) and VO_{2peak} were measured using a continuous, incremental running protocol on a horizontal, motor driven treadmill.

Electromyographic activity and stride parameter measurements

Before the start of testing, each subject had bipolar EMG electrodes (Beckman miniature skin electrodes, Illinois, USA) placed onto the *vastus lateralis* (VL), *vastus medialis* (VM), *rectus femoris* (RF), *biceps femoris* (BF) and *gastrocnemius* (GA) muscles of the right leg. The skin was shaved, rubbed with sandpaper and cleaned with alcohol. The electrodes were positioned longitudinally on the belly of each muscle and carefully taped. All EMG data were recorded telemetrically (Biomes 2000, Glonner, Germany) during each running test on the track with a laptop computer using Labview 5.1 (National Instruments, Texas, USA). The telemetric system was carried on the waist of the subject with a specially designed belt. The EMG signal was amplified (band-pass cut off frequency was 10 - 550Hz) and digitised at the sampling frequency of 1000Hz by an on-line computer system. The non-smoothed EMG signals were full wave rectified, integrated (μVxs) and time normalized (Average EMG, AEMG) for the two phases of running: pre-activation (100 ms before ground contact) and total ground contact time.

In order to measure stride parameters, a photocell contact mat[39] and two photocell gates connected to an electronic timer (Newtest, Ltd, Oulu, Finland) were placed on the final straight of the track. During the 5000m time trial, average velocity, ground contact times and flight times were measured with the photocell contact mat from a 20m section at every other lap simultaneously with EMG from the VL, VM, RF, BF and GA. Stride frequency ($strides \cdot s^{-1}$) was calculated by using contact times (CT) and flight times (FT) as $(CT + FT)^{-1}$. Stride length was calculated by dividing the average velocity by the stride frequency. Both EMG and stride parameter data collected during each stride were averaged for the number of strides taken along the 20m straight during each running test.

Maximal 20m sprint test

The subjects performed three to five maximal 20m sprints on the indoor track. They were

Table 1: Descriptive and performance characteristics of the runners (n = 18) (Body fat was calculated using the equation of DURNIN & WOMERSLEY[8]. Abbreviations: Training = average training volume from the last three months; VO_{2peak} = peak oxygen uptake; PTRS = peak treadmill running speed; T_{5K} = average time in a 5000m time trial)

Variable	Mean ± SD	Min - Max
Age (years)	23.4 ± 6.6	16 - 34
Stature (m)	1.69 ± 0.05	1.61 - 1.80
Body mass (kg)	59.6 ± 4.7	50.3 - 67.1
Body fat (%)	10.7 ± 3.0	6.6 - 17.7
Training ($km \cdot week^{-1}$)	95 ± 27[a]	70 - 160
T_{5K} (min:s)	16:58 ± 1:12	15:44 - 19:23
PTRS ($km \cdot h^{-1}$)	20.8 ± 1.2	19.0 - 23.5
VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	64.0 ± 4.0	56.3 - 70.7
a n = 17		

able to accelerate 15m before the start of the sprint to ensure a normal and maximal running gait throughout the 20m. Each sprint was separated by a 1 - 2 min recovery period during which the runners returned to the start of the sprint course. The sprints were measured using two photocell gates connected to an electronic timer (Newtest Ltd, Oulu, Finland). The fastest performance of each subject was chosen for all subsequent data analysis.

Maximal voluntary contractions

Ten minutes after completing the final 20m sprint, subjects performed three five-second maximal voluntary contractions (MVC) separated by five seconds rest on a custom-built seated leg press machine (Hur Ltd., Kokkola, Finland) with a knee flexion angle of 70°. Subjects were asked to exert maximal force with both legs against the footplate for five seconds during which standardised verbal encouragement was provided by the investigators. The single five-second contraction that produced the highest force was taken as the non-fatigued, pre-5000m time trial value, and was thus used for all subsequent data analysis. The EMG activity was analysed from the VL, VM, RF and BF muscles of the right leg in the MVC. The non-smoothed EMG signals were full wave rectified, integrated and time normalised (AEMG) for the period of two seconds during the plateau phase of the force. Immediately after finishing the 5000m time trial, the subjects went directly to the leg press machine where they performed one five-second MVC. This test occurred within ten seconds of finishing the time trial.

5000m time trial

To reduce the possible fatigue effects induced by the leg press and 20m sprint tests, the subjects rested for 20minutes after these tests. Thereafter, they performed a 5000m time trial on a 144m indoor track. They were instructed to run as fast as possible and were provided with verbal encouragement during the run. Times were recorded for each lap and the split times at each kilometre were given to the athletes during the time trial. During the final lap, subjects repeated the maximal 20m sprint test down the straight section on the track. The signals from the EMG, photocell gates and photocell contact mat were analysed from the fastest lap at the beginning of the 5000m (228 - 545m), from the slowest lap at the end of the 5000m (3972 - 4856m) and from the last lap (4980 - 5000m) when the runners entered the appropriate 20m section of track. The average EMG values were calculated for all the muscles during the ground contact and the 100 ms preactivity phase.

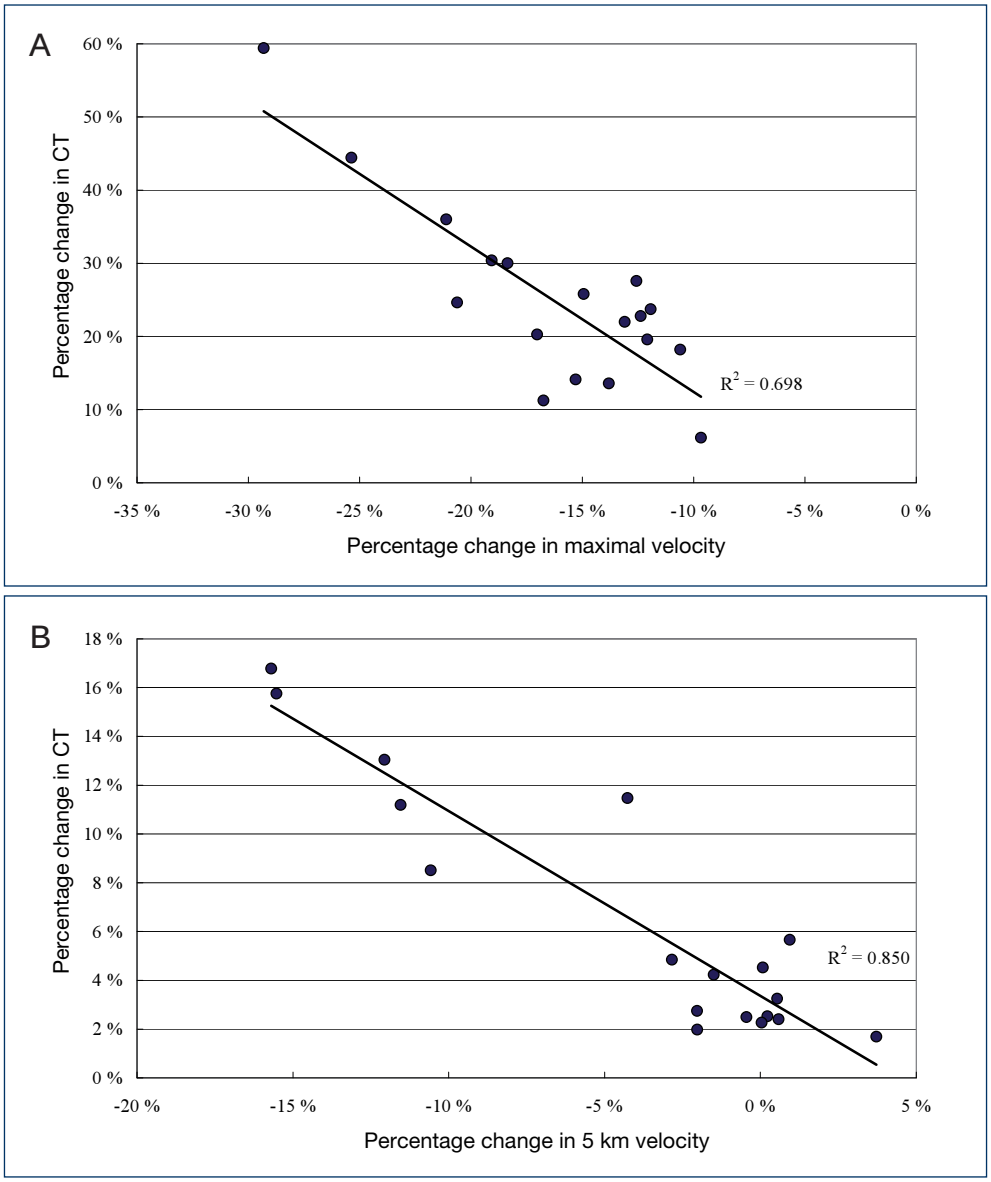

Figure 1: Percentage change in ground contact time and maximal 20m velocity (A) and velocity during a 5000m time trial (B)

Incremental exhaustive treadmill test

After a brief warm up, the runners began running at 12 km·h^{-1}. The speed was increased by 0.5 km·h^{-1} every 30 sec thereafter[33]. Oxygen consumption (Cosmed K4 RQ, Rome, Italy) and heart rate (Vantage XL Polar Electro, Finland) were measured continuously during the test. The test continued until the runner was unable to maintain the pace of the treadmill. VO_{2peak} was defined as the highest oxygen consumption during the test over a 60 sec period. The PTRS was defined as the fastest running speed the subject could maintain for 30 sec.

Table 2: The changes in stride characteristics and AEMG in the maximal 20m sprint, the maximal voluntary contractions (MVC) and during the 5000m time trial (Abbreviations: CT = ground contact time; SF = stride frequency; SL = stride length; AEMGcontact = average EMG of all measured lower limb muscles during ground contact or MVC; AEMGpre-activity = average EMG of all lower limb muscles during 100ms before ground contact; RF = rectus femoris; VL = vastus lateralis; VM = vastus medialis; GA = gastrocnemius; BF = biceps femoris)

	Start 5000m	End 5000m	Pre 20m	Post 20m	Pre MVC	Post MVC
Force (N)					900 ± 238	756 ± 218**
Velocity ($m \cdot s^{-1}$)	5.21 ± 0.29	4.74 ± 0.39***	7.61 ± 0.44	6.36 ± 0.36***		
CT (ms)	207 ± 15	220 ± 15***	139 ± 16	172 ± 12***		
SF (Hz)	3.09 ± 0.16	3.06 ± 0.15	3.89 ± 0.22	3.41 ± 0.14***		
SL (m)	1.62 ± 0.11	1.57 ± 0.13*	1.95 ± 0.09	1.87 ± 0.10***		
$AEMG_{contact}$ (µV)	0.79 ± 0.21	0.71 ± 0.19**	1.33 ± 0.41	1.00 ± 0.31***	0.79 ± 0.32	0.67 ± 0.24*
$AEMG_{VLcontact}$ (µV)	0.21 ± 0.07	0.21 ± 0.07	0.33 ± 0.10	0.26 ± 0.06***	0.27 ± 0.11	0.24 ± 0.09*
$AEMG_{RFcontact}$ (µV)	0.06 ± 0.02	0.06 ± 0.02	0.10 ± 0.03	0.08 ± 0.02***	0.16 ± 0.08	0.12 ± 0.07**
$AEMG_{VMcontact}$ (µV)	0.27 ± 0.06	0.25 ± 0.04	0.40 ± 0.06	0.34 ± 0.07***	0.34 ± 0.12	0.29 ± 0.09
$AEMG_{BFcontact}$ (µV)	0.10 ± 0.06	0.07 ± 0.04**	0.28 ± 0.10	0.16 ± 0.08***	0.04 ± 0.02	0.03 ± 0.01**
$AEMG_{GAcontact}$ (µV)	0.22 ± 0.05	0.18 ± 0.05***	0.37 ± 0.09	0.26 ± 0.06***		
$AEMG_{pre-activity}$ (µV)	0.56 ± 0.14	0.51 ± 0.13*	1.41 ± 0.48	0.80 ± 0.27***		
$AEMG_{VLpre-activity}$ (µV)	0.10 ± 0.04	0.09 ± 0.03	0.36 ± 0.15	0.16 ± 0.07***		
$AEMG_{RFpre-activity}$ (µV)	0.03 ± 0.01	0.03 ± 0.01	0.10 ± 0.04	0.06 ± 0.03***		
$AEMG_{VMpre-activity}$ (µV)	0.14 ± 0.03	0.12 ± 0.04**	0.41 ± 0.12	0.21 ± 0.07***		
$AEMG_{BFpre-activity}$ (µV)	0.24 ± 0.07	0.24 ± 0.07	0.40 ± 0.13	0.29 ± 0.09***		
$AEMG_{GApre-activity}$ (µV)	0.08 ± 0.03	0.06 ± 0.04*	0.27 ± 0.12	0.14 ± 0.05***		

* Significant difference between the start and end or between the pre and post values. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Data analysis

All the statistical analyses were done using SPSSWIN 13.0 (SPSS, Inc., Chicago, ILL, USA). Analysis of variance (ANOVA) for repeated measures was used to evaluate changes before and after the 5000m time trial and changes between the beginning and end of the time trial. Pearson's product moment correlation coefficient determined relationships between variables. Values are expressed as mean ± standard deviation or standard error. Statistical significance was accepted as $p < 0.05$.

Results

The descriptive data of the runners are shown in Table 1.

In Table 2 it can be seen theat the maximal 20m velocity decreased 16.3 ± 5.2% after the 5000m time trial ($p < 0.001$). The relative decrease in maximal velocity after the fatiguing time trial was similar to the decrease in average force (15.1 ± 14.9%) in the maximal leg press ($p < 0.01$). In the time trial the decrease in the velocity from the highest velocity at the beginning to the slowest velocity at the end of the 5000m was 9.9 ± 6.3% ($p < 0.001$). The velocity loss during the time trial did not correlate with either the decrease in maximal 20m velocity ($r = 0.24$) or the decrease in the average force of the MVC ($r = 0.03$). Furthermore, no significant correlation existed between the decrease in maximal 20m velocity and the decrease in the average force of the MVC ($r = 0.43$).

The changes in stride characteristics and AEMG in the maximal 20m sprint, in the MVC and during the 5000m time trial are also shown in Table 2. Figure 1 shows that the decrease in velocity was correlated significantly with the increase in the ground contact time both in the maximal 20m sprint ($r = -0.84$, $p < 0.001$) and during the time trial ($r = -0.92$, $p < 0.001$). Although the AEMG during the pre-activation and total ground contact phase decreased in the maximal 20m sprint and during the 5000m time trial, the decreases in the AEMG were not related to the decrease in velocity. However, as shown in Figure 2, the changes in the AEMG during the pre-activation were related to the changes in ground contact time ($r = -0.80$, $p < 0.001$) and stride frequency ($r = 0.79$, $p < 0.001$) in the maximal 20m sprint. Similar relationships, although not significant, were observed during the 5000m time trial (Figure 2). Furthermore, the decreased average force in the MVC was related to the decrease in the AEMG ($r = 0.82$, $p < 0.001$).

The correlation coefficients between the selected variables of training and performance characteristics of the runners show that the fatigue in the maximal 20m sprint was related to the maximal running velocity but not to the volume of training or the performance in the 5000m time trial (Table 3). The fatigue during the 5000m time trial was related to the relative velocity (% of PTRS) in the beginning of the time trial, the volume of training and the performance in the time trial (Table 3). The fatigue in the MVC was only related to the relative velocity (% PTRS) in the beginning of the time trial but not to any training or performance characteristics of the subjects (Table 3). As shown in Figure 3, the correlation coefficient between the average velocity in the 5000m time trial and average lap velocity increased gradually during the first kilometre of the time trial and remained above $r = 0.90$ from 900m until it decreased to 0.61 during the final lap.

Discussion

These data suggest that this group of athletes displayed a relatively wide range of both anthropometrical and performance variables. Several studies have measured knee extensor muscle isometric strength loss after prolonged exercise. After running exercise for longer than two hours the loss of strength increases as a non-linear function of the exercise duration[20]. The isometric strength loss in the present study was 15%, which is somewhat lower than that in running exercises of longer duration shown in a previous study and therefore it was in accordance with the finding of MILLET & LEPERS[21]. We observed a decrease in velocity (16%) in the maximal 20m sprint after the 5000m time trial similiar to the

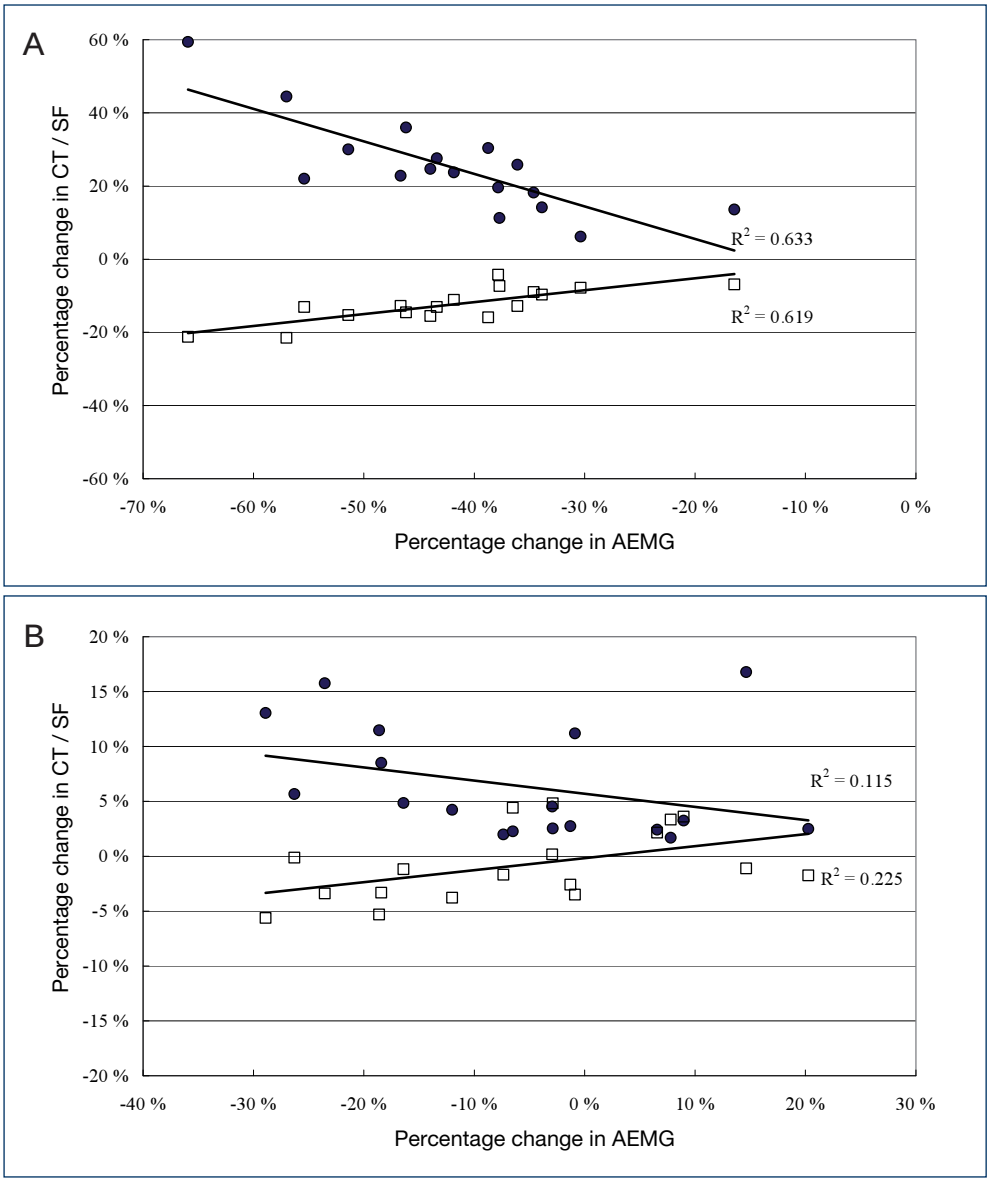

Figure 2: Percentage change in ground contact time (dots) and stride frequency (squares) and average EMG during pre-activity phase in the maximal 20m sprint (A) or during the 5000m time trial (B)

decrease in force in the MVC (15%). In the previous study, the decrease in the maximal velocity was 23% after a 10,000m time trial in the well-trained endurance athletes[31].

The first interesting and remarkable finding of the present study was that the changes in the average force of the MVC, the maximal velocity of the 20m sprint test and the decrease in velocity during the 5000m time trial were not related to each other. The strongest relationship (r = 0.43) existed between the changes in maximal exercises before and after the 5000m, but this did not

Table 3: Correlation coefficients between selected training and performance characteristics and fatigue during the 5000m time trial, in the maximal 20m sprint and in the maximal voluntary contractions (MVC). Abbreviations: V_{5km} = velocity in the 5000m time trial, V_{20m} = velocity in the maximal 20m sprint, VO_{2peak} = peak oxygen uptake, V_{start} = the highest velocity at the beginning of the 5000m.

	% change in V_{5km}	% change in V_{20max}	% change in F_{MVC}
V_{5km} ($m \cdot s^{-1}$)	-0.60**	-0.21	0.31
V_{20m} ($m \cdot s^{-1}$)	0.03	0.58*	0.16
VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	-0.49*	-0.50*	0.19
Training volume (km)	-0.58*	0.06	-0.08
Vstart ($m \cdot s^{-1}$)	0.61*	-0.12	0.48*

* p < 0.05, ** p < 0.01, ***

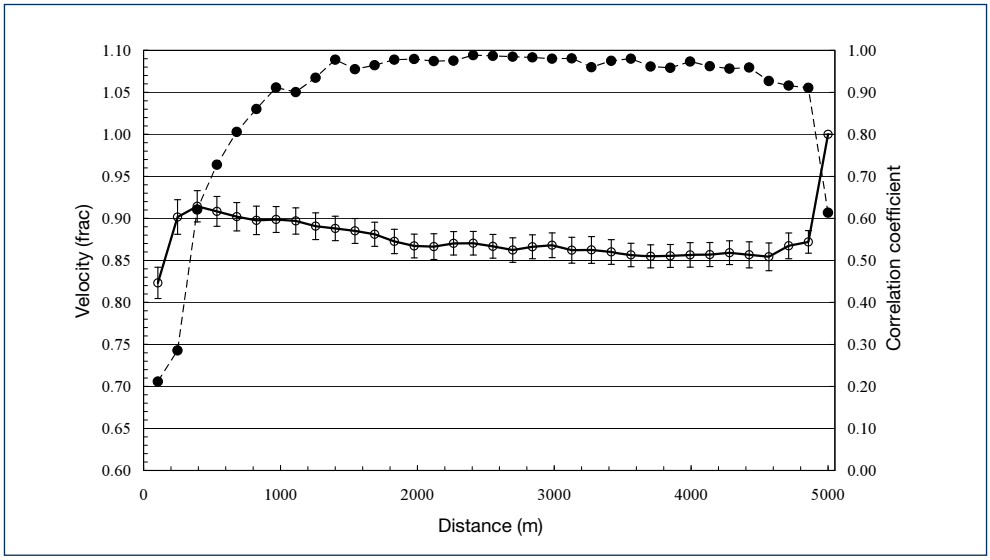

Figure 3: The relative velocity (open circles) during the 5000m time trial and correlation coefficients between the average lap velocity and average velocity (dots) (Relative velocities are expressed as mean ± SE)

reach the level of significant. In the MVC and maximal 20m sprint tests the force or velocity loss was not related to the performance in the 5000m. This finding supports the results of PAAVOLAINEN et al.[31] who found that the decrease in velocity in the maximal running test after a 10,000m time trial was not related to the performance in the time trial. However, the decrease in velocity from the beginning to the end of the 5000m time trial was related to the performance in the 5000m. An interpretation of these results is that the type of muscular contraction and type of test (i.e. MVC vs. 20m sprint vs. 5000m self paced) determine the reduction in strength and power. Since the fatigue results of MVC were not related to any measured performance abilities, it is questionable to use an isometric test as an indicator of fatigue for runners.

As shown in Table 3, the fatigue in the MVC was not related to any measured perform-

ance abilities. The velocity decrease in the maximal 20m sprint correlated positively with the maximal 20m velocity before the 5000m and negatively with the VO_{2max} suggesting that the maximal running velocity decreased most in the athletes who had the best sprinting abilities and the lowest maximal oxygen uptake. This confirms earlier findings, which have shown that sprint and middle-distance runners, who had higher power output and lower endurance abilities, showed greater fatigability than long-distance runners[29, 40]. This could be explained at least partly by fibre type composition, since athletes with high percentage of fast-twitch fibres are more susceptible to fatigue than athletes with a high percentage of slow-twitch fibres[36].

The decrease in velocity during the 5000m was positively correlated with the initial velocity of the 5000m, negatively correlated to the training volume (recorded for the three months preceding the tests) and to the VO_2max suggesting that initial velocity and endurance abilities affect the velocity loss or fatigue resistance during the 5000m. The present results suggest that the fatigue in the maximal 20m sprint test was more dependent on the fast-twitch muscle fibres, utilisation of anaerobic energy sources and ability to produce power than the velocity loss during the 5000m, which was more dependent on the endurance characteristics. This may also explain the shape of the velocity curve and the remarkable increase of velocity (34%) at the end of the time trial, when the runners should have been most fatigued. This suggests that the runners had the ability to increase their velocity at any time during the 5000m but their pacing strategy controlled this to prevent premature exhaustion[38].

The pacing strategy in the present study was freely chosen by the athletes. They were only asked to run 5000m as fast as possible and to run the last 20m at their maximal effort. Furthermore, the laps were counted for the athletes and split times at each kilometre were given to the athletes during the time trial. The average velocity curve of the athletes was typical in the 5000m run, which is characterised by fast starts, a period of slower running during the middle of the race, and followed by a significant increase in speed towards the end[38]. This is similar to the pacing strategies adopted by elite rowers during 2000m rowing races and time trials[10]. ST CLAIR GIBSON et al.[35] have stated that the most important factor allowing the establishment of the pacing strategy is knowledge of the endpoint. However, the pacing strategy is also affected by the environmental conditions, the motivation of the athlete, the knowledge and experience of the athlete, and each athlete's particular physiological capacity. The environmental conditions were constant in the present study, since the tests were performed on an indoor track with controlled environmental conditions. The motivation of the runners was not measured but they were all verbally encouraged during the whole run. The knowledge of split times at each kilometre may also affect motivation and pacing strategy of the athletes, but this seems to have only a minor effect since the typical velocity profile for 5000m was observed in the present study.

The velocity at the beginning of the 5000m was affected by the experience of the runners in the present study. The experience of the runners can be evaluated by the level of 5000m performance and training volume so that more experienced runners had better distance running performance and trained more than the runners with less experience. We observed that the runners who had better 5000m performance and higher training volume during the three months preceding the tests started the 5000m at relatively lower velocity (% PTRS) and they had more constant pacing during the 5000m, since a significant correlation was observed between the high initial velocity and velocity loss during the time trial. The correlation coefficients between the lap velocities and 5000m performance in Figure 3 supported this finding, since the initial velocity was poorly correlated with the 5000m performance in this group of athletes.

In order to maintain and alter the running pace during the 5000m time trial, the brain must process an enormous quantity of data from the external conditions and from the various physiological systems of the body. From the beginning of the run, this afferent information is used to set and alter the appropriate pace control algorithm for the rest of the time trial as suggested by ST CLAIR GIBSON et al.[35]. An example of the runner's physiological limits and successful pacing algorithm can be seen in the middle part of the 5000m time trial (Figure 3) where there were high correlation coefficients ($r > 0.90$) between the lap velocities and 5000m performance.

The reduced EMG activity and velocity during the 5000m time trial supports the idea that in longer duration events the pacing strategy is regulated to ensure that a reserve is present at the end. Therefore running speed can be increased consequent to an increase in skeletal muscle recruitment at the end of the run. In the present study, this was shown as an increased EMG activity at the end of the 5000m time trial. The phenomenon seems to be different in short-duration runs like the 400m[27, 28] and long-duration runs like the triathlon and marathon[11]. In 400m time trials, the running velocity decreased progressively even though motor unit activation (measured as EMG activity) was able to increase to compensate for the apparent failure of contractility[27]. This could be explained by the differences in pacing strategy and by the use of anaerobic energy sources. In optimal pacing strategy for short-term maximal exercises like the 400m, the velocity decreased throughout the exercise and there is no need for a reserve at the end of the run. A possible reason for the difference between 5000m and marathon running is that muscle fatigue and strength loss is greater in longer events, as suggested by MILLET & LEPERS[20], and athletes are not able to increase their running velocity at the end of the marathon to the same extent as they do at the end of the 5000m. This greater strength loss in a marathon requires that the athletes must compensate by increasing their motor unit activation.

Another important finding of this study was that the AEMG during both the pre-activation and the ground contact phase of the lower limb muscles decreased during the 5000m time trial. These findings are similar to those after a 400m sprint[28], a 10,000m time trial[31] and a marathon[21]. Similarly, the AEMG during the MVC decreased after the 5000m time trial. Force and EMG have also decreased after fatiguing maximal leg extensions[18], high intensity cycling[5], and after a 65km footrace[19]. These studies have concluded that the reduction in EMG and the corresponding decrease in isometric force represent a form of central fatigue. However, this explanation is not absolutely established, since the sarcolemmal excitability can also be modified[32]. The reduced EMG activity in the maximal situation can be explained by spinal and supraspinal factors[9]. The reduced activity can be caused by a failure to generate output from the motor cortex or by an alteration in input from muscle spindle, Golgi tendon organ, and group III and IV muscle afferents innervating the fatiguing muscle, or both.

The contribution of the spinal and supraspinal changes to fatigue was not measured in this study, but we observed a clear EMG reduction in the pre-activation phase during running. AVELA & KOMI[2] observed that the reduced EMG activity in the soleus and vastus medialis muscles were more pronounced in the pre-activation and eccentric phases compared to the concentric phase after the fatiguing marathon run. It has been agreed that the pre-activation phase is strongly pre-programmed and controlled by higher supraspinal centres[1]. Thus our findings may suggest that some level of supraspinal fatigue was present. HORITA et al.[12] have found that in drop jump exercises muscle pre-activity correlated with muscle stiffness during the initial phase of contact. This relationship suggests that pre-activation regulates the force production in drop jumps as demonstrated by the high series elastic component stiffness, the short contact time and more economical work[12]. In the present study, the decreased pre-activation and a significant correlation

between the decreased pre-activation and increased contact times suggest that changes in stiffness regulation may play a role in reducing maximal running speed during and after the 5000m time trial. Similar findings were also observed in the fatigue that developed after a 10,000m time trial[31]. The authors found a decreased pre-activation and a significant relationship between the decreased pre-activation and decrease of horizontal ground reaction force in the braking phase.

In conclusion, the results of the present study showed that muscle fatigue measured in maximal exercises like a 20m sprint and MVC are not related to the velocity loss during a 5000m time trial. The results of fatigue depend on the type of the measurements, and whether the fatigue is measured pre- and post-exercise or during the fatiguing exercise. The fatigue in 5000m running measured pre- and post-exercise at maximal effort is more related to sprint performance rather than endurance performance, but the fatigue measured during 5000m running is related to endurance performance and factors affecting pacing strategy. We propose that the present findings support the idea that pacing strategy is regulated in an anticipatory manner by a central governor[23, 24], which ensures that physiological reserves are maintained.

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