Journal of Strength and Conditioning Research, 2002, 16(2), 184–191
© 2002 National Strength & Conditioning Association

The Effects of a 10-Kilometer Run on Muscle Strength and Power

ANA L. GÓMEZ,[1] ROBERT J. RADZWICH,[2] CRAIG R. DENEGAR,[2] JEFF S. VOLEK,[1] MARTYN R. RUBIN,[1] JILL A. BUSH,[2] BRANDON K. DOAN,[3] ROBBIN B. WICKHAM,[3] SCOTT A. MAZZETTI,[3] ROBERT U. NEWTON,[3] DUNCAN N. FRENCH,[1] KEIJO HÄKKINEN,[4] NICHOLAS A. RATAMESS,[1] AND WILLIAM J. KRAEMER[1]

[1]Human Performance Laboratory, Department of Kinesiology, The University of Connecticut, Storrs, Connecticut 06269; [2]Laboratory for Sports Medicine, Department of Kinesiology, Center for Sports Medicine, Pennsylvania State University, University Park, Pennsylvania 16802; [3]The Biomechanics Laboratory, Ball State University, Muncie, Indiana 47306; [4]Neuromuscular Research Center, Department of Biology of Physical Activity, The University of Jyväskylä, Jyväskylä, Finland.

ABSTRACT

Recovery of maximal force and power following a 10-km race has not been widely studied in the scientific literature. Ten healthy men who were experienced distance runners participated in this investigation. Data were collected prerace, immediate postrace, and 48 hours postrace to examine the effect of a 10-km race on muscle force production in the lower body. Maximal peak torque was measured via an isokinetic dynamometer at 30°, 180°, and 300°·s^{-1}. A significant ($p \leq 0.05$) reduction in peak torque for knee flexion was observed at 30°·s^{-1} immediately postrace. Average power of the knee flexors were significantly decreased immediately postrace. Total work (J) flexion performed over the last 17 repetitions of the 50-repetition test were significantly reduced from baseline values during both the immediate and 48-hour postrace tests. Significant reductions in peak vertical jump force remained reduced 48 hours postrace testing. No changes were observed for jump power after the race. These data indicate that only the hamstring muscle group was not fully recovered to perform the 50-repetition test and that force production in the vertical jump test was compromised 48 hours after a 10-km race. Nevertheless, it appears that strength and power capabilities of the 10-km runner are for the most part restored 48 hours after an all-out 10-km race effort. From a practical perspective, it appears that a minimum of 48 hours should be utilized between multiple trials in 10-km races at track and field meets.

Key Words: endurance running, physical performance, recovery

Reference Data: Gómez, A.L., R.J. Radzwich, C.R. Denegar, J.S. Volek, M.R. Rubin, J.A. Bush, B.K. Doan, R.B. Wickham, S.A. Mazzetti, R.U. Newton, D.N. French, K. Häkkinen, N.A. Ratamess, and W.J. Kraemer. The effects of a 10-kilometer run on muscle strength and power. *J. Strength Cond. Res. 16(2):184–191. 2002.*

Introduction

In track and field meets at higher level competitions, multiple 10-km races are needed to narrow the field of competitors. Recovery between races is typically 48 hours. Maximal effort is many times required by many runners to make the finals. To date, no data exist as to the impact of such an effort over the 10-km distance on force production capabilities of muscle. Furthermore, the pattern of recovery remains unclear.

Long-distance racing of distances 20 km and greater have been reported to significantly decrease muscle strength and/or exercise capacity (i.e., multiple isokinetic repetitions, such as 50–60 repetitions) following competition (29, 31). This may be because of both muscle damage and glycogen depletion, which would be greater in the longer distances (i.e., marathon and longer; 1, 3, 10, 12, 15). Although depletion of some muscle glycogen may occur during shorter race distances performed at faster speeds, it would not appear to be a primary limitation in strength and power capabilities following the race (9, 23). Furthermore, strength and power capabilities of the lower-body musculature may be more important for faster races (e.g., 10 km).

Kraemer et al. (29) observed decreases in area under the peak torque curve following a 20-km race-pace treadmill run while maximal peak torque in the knee flexor/extensors were not affected. The authors speculated that the 20-km race did not significantly affect the fast-twitch motor units responsible for peak torque

Table 1. Subject characteristics and descriptive data.

Subject	Age (yr)	Height (cm)	Weight (kg)	Body fat (%)	$\dot{V}_{O_2}$max ($ml \cdot kg^{-1} \cdot min^{-1}$)
1	21	180.34	73.18	9.85	58.45
2	24	185.42	82.72	8.39	59.00
3	18	175.26	63.63	9.49	63.55
4	23	170.18	61.36	9.12	75.75
5	26	175.26	70.45	13.20	61.20
6	23	187.96	81.36	7.96	64.70
7	25	170.18	62.72	5.62	62.75
8	22	185.42	73.18	7.60	64.80
9	22	177.80	70.45	11.86	64.85
10	18	182.88	74.09	9.38	63.30
Mean ± *SD*	22.2 ± 2.6	179.1 ± 6.4	71.3 ± 7.3	9.3 ± 2.1	63.8 ± 4.8

production, whereas the reduction in the area under the peak torque curve was due to the fatigue of the slow motor units (7, 21, 22). With the marathon distance, Sherman et al. (31) reported significant reductions in isokinetic strength and exercise capacity immediately after a marathon race. Interestingly, these measures did not return to baseline value until 3 days postmarathon. This may have been because of muscle damage typically consequent to the marathon race (13, 31).

One might hypothesize that force production of muscle would not be affected if the race was comparable to a 20-km race and just recruited slow-twitch motor units (i.e., low threshold; 8, 11, 21). However, we thought that with faster speeds, more higher-threshold motor units would be recruited to run the race. In addition, we hypothesized that some damage would occur with a maximal effort competition over this period of time. Thus in general we hypothesized that a reduction in force production capabilities would be observed after the 10-km race. Any changes in the immediate postrace force production results should be reflective of acute fatigue associated with the race, and if changes persisted over 48 hours of recovery this may be reflective of chronic fatigue associated to the contractile unit. If an athlete is to be in optimal condition for a competitive race, recovery of strength and power would appear important for a runner when maximal efforts (e.g., kick phases of a race) play a role in competitive success (25, 26).

Recovery may be even more important for those athletes that race at high percentages of their personal record performances to reach the finals. Therefore, the purpose of this investigation was to examine the strength and power capabilities and the pattern of muscular recovery over 48 hours after a 10-km race.

Methods

Experimental Design and Approach to the Problem

In order to examine this problem we recruited competitive 10-km recreational runners to participate in a race to achieve a personal record. It was important that the race was run as close to a maximal effort as possible in order to draw conclusions as to the changes in force production in the upper thigh and closed kinetic chain. Testing was conducted before, immediately after, and 48 hours postrace to determine the impact of 2 days of recovery commonly used in meets where preliminary heats are needed to qualify for the finals.

Subjects

The 10 men were recruited from local area track clubs. All runners were experienced competitors training for 10-km races, and many were former collegiate endurance athletes. The study was approved by a University Institutional Review Board for use of human subjects in research. Subjects were informed of the potential risks and benefits of the study, and each provided written informed consent. Subjects were screened by a physician, were not to take any medication, and were free of any orthopedic or medical conditions that would confound the interpretation of the data. The nutritional intake of all subjects consisted of adequate energy requirements from carbohydrates, fats, and protein prior to the race and after the race in order to optimize substrate recovery (2). The subject characteristics and other descriptive data are shown in Table 1.

Experimental Design

A battery of strength and power performance tests were administered in this investigation. Subjects were thoroughly familiarized with the experimental test protocol prior to the investigation. This included several practice sessions to reduce potential learning effects (17). Test batteries were administered at 3 time points: 2 days prerace, within 15 minutes postrace (runners were transported by car to a testing facility that was within one-half mile from the track), and 2 days postrace. Baseline testing was performed 2 days before the race to assure a maximal effort. Our previous pilot experience with runners was that testing right before the race tended to produce lower force

production values because of what might be postulated as inhibitory effect and psychological fear of injury and the desire to protect their subsequent race performance. The order of testing was a vertical jump power test, isokinetic testing, and a repetitive isokinetic endurance test. Test-retest reliabilities for all experimental tests done in this same order demonstrated intraclass correlations of $R \geq 0.94$.

Experimental Race

A competitive 10-km race for the subjects was held on a standard, all-weather, 400-m competitive outdoor track. Each subjects' individual time was obtained as well as a pre- and immediate postrace heart rate through radial palpation. Postrace rating of perceived exertion using the Borg scale (6–20) was obtained following the race to assess effort in addition to race time (5, 6). The goal of the race for each subject was to set a personal record. Individual time keepers were used for each subject.

Isokinetic Testing

A System II Biodex isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, NY) with a graphic recorder and computer software was used to measure peak torque and to determine the area under the peak torque curve. The isokinetic dynamometer was calibrated prior to each testing session according to the procedures prescribed by the manufacturer (4). During testing, subjects were stabilized at the thigh, chest, and with waist straps. The velocities utilized were as follows: 30°, 180°, and $300°\cdot s^{-1}$. These velocities were chosen to provide for a common velocity profile of torque production capabilities. Strength was defined as the highest maximal voluntary isokinetic peak torque at each of the 3 speeds for knee extension and flexion movements. Maximal concentric peak torque was the highest torque value produced from 3 individual efforts (17).

Isokinetic Endurance Test

The endurance test consisted of performing voluntary maximal isokinetic knee extension and flexion movements for 50 repetitions at $180°\cdot s^{-1}$ (29, 32). Subjects were instructed to perform maximal knee extension and flexion as fast as possible for the entire 50-repetition test. Subjects were instructed not to pace themselves. Muscular endurance was defined as the expression of total work (J; area under torque curves) during repetitive extension and flexion movements for 50 repetitions. Total work and average power were determined by computer analysis of the entire 50-repetition torque. Repetitions 1–17 and repetitions 34–50 were analyzed to assess fatigue during the early and later phases of the endurance test.

Jump Power Tests

A standing countermovement vertical jump test was used to determine maximal vertical jump power. An AMTI (Advanced Medical Technology Inc., Watertown, MA) was utilized for force plate measurements to determine power. After a proper warm-up, each subject performed 3 trials of a maximal countermovement vertical jump on the force plate with his hands on the waist. The highest value obtained was used for data analysis. Computer analysis of force time curves allowed determination of peak force and power. Time to peak power development was also determined.

Aerobic Power Test

For descriptive purposes, maximal oxygen consumption was determined using a graded exercise test on a Quinton (Seattle, WA) motor-driven treadmill using a modified Bruce protocol to volitional fatigue (30). During each stage of the test, heart rate was monitored continuously via a Polar Heart Rate Monitor, and ratings of perceived exertion (RPE) were recorded each minute. Expired gases were analyzed during the last 6 minutes of the test using an automated metabolic system. The gas analyzers consisted of a Beckman LB-2 CO_2 analyzer (Beckman Instruments, Schiller Park, IL) and S3A O_2 analyzer (Applied Electrochemistry, AEI Technologies, Pittsburgh, PA) and were calibrated with standard gases prior to each test. Standard gas mixtures used to calibrate the gas analyzers were previously calibrated via Scholander methodology. Flow was measured by a Hans Rudolph model 4813 Pneumotach and transduced to volume by a Fitco Micro-Flow model FLO-1 instrument. These signals were integrated in a software package by Fitco (Farmingdale, NY).

Anthropometric Measures

Typical anthropometric and descriptive measures (e.g., age, height, and weight) were obtained from each subject. Body density was estimated using 7 skinfolds taken with a Lange skinfold caliper (Country Technology, Gay Mills, WI) according to the methods by Jackson and Pollock (27). The 7 sites were the triceps, subscapula, suprailiac, thigh, midaxilla, abdomen, and chest. Percent body fat was calculated using the Siri equation. Three skinfolds taken at each site and a variance of less than 5% was an acceptable criterion for measurement. Body weight was measured to within 0.1 kg using a calibrated scale with the subjects wearing only shorts.

Statistical Analyses

These data were analyzed using a 1-way analysis of variance (ANOVA) with repeated measures and Fisher least significant difference post hoc when appropriate. Significance in this study was set at $p \leq 0.05$.

Results

The purpose of this investigation was to examine the effects of an all-out 10-km race on the recovery of mus-

Table 2. Data from the 10-km run.

10-km subject	Post run time (min:s)	Final 10-km heart rate	10-km RPE*
1	35:03	198	15
2	36:41	183	18
3	32:22	210	19
4	35:33	186	16
5	35:35	180	18
6	32:59	164	17
7	35:12	180	18
8	35:21	186	19
9	37:09	168	18
10	36:02	184	17
Mean ± *SD*	35:12 ± 1:28	184 ± 13	17.5 ± 1.3

* RPE = ratings of perceived exertion.

cle strength and power capabilities following the race. The efficacy of this study was primarily dependent on a maximal effort of each subject during the simulated 10-km race. Testing was conducted prior to the experimental race, immediately postrace, and at 48 hours postrace. The order of testing was identical each time and was initiated within 10 minutes after the race.

The 10-km race times for this study ranged from 32:22 to 37:09, which, as a group, represented a 98% effort according to their pre-established personal records. The postrun heart rate ranged from 164 to 210 $b \cdot min^{-1}$, representing an average of 98% of the maximal heart rate obtained from the maximal aerobic power test. The ratings of perceived exertion obtained immediately after the subjects finished the race ranged from 15 to 19 on the Borg scale. These data indicate that the experimental 10-km race was run at an intensity and pace that may be representative of an all-out effort in a 10-km race, thus making the findings of this study applicable to the recovery process after maximal-effort 10-km races. As a group, the subjects averaged 34:16 ± 1:47 for their previous personal bests and ran the 10 km for this study in 35:12 ± 1:28. Table 2 shows the race performance results.

Isokinetic Peak Torque

Peak torque of the knee extensors and flexors before, immediately postrace, and 48 hours postrace are presented in Tables 3, 4, and 5. Peak torque was measured at 30°, 180°, and $300° \cdot s^{-1}$. At $30° \cdot s^{-1}$, a significant decrease in peak torque for knee flexion immediately postrace was observed. The time to peak torque, angle of peak torque, and total work for 1 repetition showed no significant changes from pre- to postrace tests.

Isokinetic Exercise Capacity

The total exercise capacity of the knee flexors and extensor muscles were evaluated using a 50-repetition test. The results can be observed in Table 6. Total exercise capacity and the average power of the knee flexors demonstrated significant decreases immediately postrace. These values returned to baseline levels at the 48 hour postrace time point. In addition, the total flexion work done over the last one-third of the endurance test was significantly decreased, whereas the total flexion work for the first two-thirds of the endurance test demonstrated no changes. There was a noticeable but not significant decrease in the total exercise capacity of the knee extensors from prerace to both postrace

Table 3. Isokinetic testing results for knee extension and flexion at $30° \cdot s^{-1}$.*

	Peak torque (Nm)		Time to peak torque (ms)		Total work (1 repetition)	
	Extension	Flexion	Extension	Flexion	Extension	Flexion
T1†	246.2 ± 30.1	140.8 ± 22.5	768 ± 304.4	533 ± 107.4	149.4 ± 30.8	232.3 ± 46.4
T2	237.4 ± 34.1	131.9 ± 18.9*	869 ± 271.6	507 ± 198.6	138.3 ± 19.5	216.4 ± 33.8
T3	243.6 ± 41.3	135.0 ± 15.7	809 ± 294.9	474 ± 171.6	144.3 ± 26.9	230.2 ± 41.3

* Mean ± 1 *SD*, $n = 10$, $p \leq 0.05$ from corresponding prerace values.
† T1 = baseline value; T2 = immediately postrace; T3 = 48 hours postrace.

Table 4. Isokinetic testing results for knee extension and flexion at $180° \cdot s^{-1}$.

	Peak torque (Nm)		Time to peak torque (ms)		Total work (1 repetition)	
	Extension	Flexion	Extension	Flexion	Extension	Flexion
T1*	148.0 ± 20.9	96.8 ± 17.5	212 ± 46.6	207 ± 95	124.3 ± 19.6	89.3 ± 17.5
T2	147.1 ± 22.2	99.1 ± 13	228 ± 57.7	224 ± 108.6	119.1 ± 18.6	84.0 ± 10.9
T3	145.9 ± 19.2	100.3 ± 12.9	241 ± 45.6	221 ± 159.5	122.7 ± 19.4	85.4 ± 12.2

* Mean ± 1 *SD*, $n = 10$. T1 = baseline value; T2 = immediately postrace; T3 = 48 hours postrace.

Table 5. Isokinetic testing results for knee extension and flexion at 300°·s^{-1}.

	Peak torque (Nm)		Time to peak torque (ms)		Total work (1 repetition)	
	Extension	Flexion	Extension	Flexion	Extension	Flexion
T1*	86.4 ± 12.8	64.7 ± 10.7	148 ± 30.1	207 ± 121.4	127.4 ± 18.5	88.0 ± 23.4
T2	86.3 ± 13.62	65.2 ± 9.3	148 ± 23.0	183 ± 102.1	126.8 ± 19.2	89 ± 18.2
T3	84.5 ± 12.8	65.6 ± 11.3	140 ± 20.5	203 ± 125.4	127.9 ± 20.6	84.9 ± 25.5

* Mean ± 1 *SD*, n = 10. T1 = baseline value; T2 = immediately postrace; T3 = 48 hours postrace.

tests. Endurance average power for both flexion and extension did show a significant decline for the immediate postrace test, whereas the 48-hour postrace test demonstrated no changes from the baseline value.

Vertical Jump Power Analyses

Countermovement vertical jumps were assessed by use of a force plate. The highest values obtained from 3 maximal jump attempts were used for analysis. The results can be observed in Table 7. There was a significant decrease in the peak jump force from prerace to the immediately postrace and 48 hours postrace tests. The rate of force development as measured by the time to peak jump force from force plate jump analysis demonstrated a significant decrease immediately postrace. No significant change was found in the peak jump power at any time postrace.

Discussion

This was the first study to examine the impact of a 10-km race on the recovery of muscle strength and power performances. The primary findings of this investigation demonstrate after a 10-km race that only the muscle force production in the hamstring muscle group was primarily affected. Except for the torque production in leg flexion at 30°·s^{-1} and total work for the last 17 repetitions of the fatigue test, almost all of the other force and power measures returned to baseline values within 48 hours after the race. Previous studies have examined long-distance races and have reported an acute loss of muscle function after high-intensity endurance exercise; however, examination of muscle function has been limited only to isokinetic short-term exercise measures (28, 29, 31). Sherman et al. (31) reported that a marathon severely impaired muscle function as measured by maximum peak torque and exercise capacity for knee extension movements for up to 7 days following a marathon race (31). Jacobs et al. (28) reported that when both slow-twitch and fast-twitch muscle fibers were depleted of glycogen after performing a combination of prolonged running, sprints, and maximal isokinetic contractions, peak torque at a relatively fast velocity of contraction (3.2 rad·s^{-1}) was significantly impaired. The data from the current investigation indicate that the lack of changes in our isokinetic peak torque measurements reflects the possibility that muscle glycogen was not significantly depleted after the 10-km race.

The runners in this study showed a significant decrease in isokinetic maximal peak torque for knee flexion at 30°·s^{-1} immediately postrace. The hamstring muscle group was significantly affected by the 10-km run when tested at the relatively slow isokinetic speed. No other studies have investigated maximum peak torque production at the speed of 30°·s^{-1}. Because of the slow speed of this isokinetic test that allows for contribution of the type I muscle fibers in recruitment, our results may indicate an impaired function of predominantly slow-twitch motor units (high force) in the hamstrings consequent to the race (22, 29).

Conversely, the knee extension test at 30°·s^{-1} demonstrated no significant performance detriment following the 10-km race. Sherman et al. (31) found a significant decrease in maximum peak torque at 63°s^{-1} immediately postmarathon and noted that this value stayed depressed even at 48 hours postrace. Our data viewed in context with those of Sherman et al. (31) may indicate the effect on the quadriceps is due to the duration of a marathon compared with the duration of a 10-km run. Additionally, the marathon may have contributed to an overall neuromuscular fatigue because of the much longer race duration, which again may have depleted higher amounts of muscle glycogen.

There was no significant change in both knee extension and flexion at the 180°·s^{-1} speed at either the immediate post–10-km race or 48 hours postrace. Similarly, Kraemer et al. (29) found a 20-km race-pace treadmill run to have no significant effect on knee extension at 180°·s^{-1}. However, this is contrary to the results of Sherman et al. (31), again after a marathon race saw dramatic reductions in peak torque. One might speculate that the lack of changes at the 10- and 20-km distances is due to the limited amount of glycogen depletion in the muscle fibers of the higher-threshold motor units recruited for this laboratory test (23). Thus one might conclude that the 10-km race distance does not necessarily result in any reduction of force production as observed with longer race distances.

Table 6. Isokinetic exercise 50-repetition test.†

	Total work (J)		Average power (W)		Work (J), first 17 repetitions		Work (J), last 17 repetitions	
	Extension	Flexion	Extension	Flexion	Extension	Flexion	Extension	Flexion
T1‡	3071.1 ± 393.9	2225.0 ± 324.8	137.0 ± 21.2	97.2 ± 12.7	1303.9 ± 185.4	899.1 ± 307.3	794.3 ± 102.9	548.2 ± 79.2
T2	28928 ± 469	2052.6 ± 251.8*	130.9 ± 21.0*	91.6 ± 8.1*	1252.7 ± 222.2	916.1 ± 113.0	715.8 ± 121.2*	489.0 ± 82.6*
T3	3000.4 ± 434.4	2119.6 ± 295.3	139.9 ± 21.5	97.4 ± 13.2	1269.5 ± 210.9	936.1 ± 108.8	765.3 ± 91.3	507.8 ± 101.3**

† Mean ± 1 *SD*; $n = 10$.
‡ T1 = baseline value; T2 = immediately postrace; T3 = 48 hours postrace.
* $p \leq 0.05$ from corresponding prerace value.
** $p \leq 0.05$ from corresponding immediate prerace value.

Table 7. Vertical jump analyses.†

	Peak force (n)	Peak power (W)	Time to peak force (ms)
T1‡	1758.3 ± 360.5	3149.8 ± 505.1	0.604 ± 0.2
T2	1699.4 ± 348.1*	3195.0 ± 374.6	0.719 ± 0.2*
T3	1718.9 ± 381.6**	3130.8 ± 477.8	0.623 ± 0.2

† Mean ± 1 *SD*; $n = 10$.
‡ T1 = baseline value; T2 = immediately postrace; T3 = 48 hours postrace.
* $p \leq 0.05$ from corresponding prerace value.
** $p \leq 0.05$ from corresponding immediate prerace value.

Similarly, maximum peak torque at $300°\cdot s^{-1}$ also demonstrated no significant changes after the 10-km run for both the extension and flexion tests. These results again differ from data by Sherman et al. (31) following a marathon race and may again be hypothesized to be related to the lack of residual fatigue experienced by fibers at the higher-threshold levels of activation. Alternatively, although less probable, one might hypothesize a reduced number of type II motor units utilized in the race performance (24, 29). Owing to the fact that we had hypothesized that a faster race pace would require recruitment of higher-threshold motor units to produce faster running speeds, it appears that the duration of the demands were not high enough to produce a significant depletion of energy sources. This theoretically compromised force production ability was only observed in the latter stages of the 50-repetition test in the hamstrings.

Using a 50-repetition test, the knee flexors and extensors were evaluated for total exercise capacity. Immediately postrace, total exercise capacity and average power of the knee flexors showed significant reductions. These values did, however, return to baseline at the 48-hour postrace test. Total flexion work done over the last one-third of the endurance test was significantly reduced and remained below baseline both immediately postrace and 48 hours postrace. The value of endurance average power for extension and flexion showed a significant decline immediately after the 10-km run. This value did return to baseline upon retest 48 hours postrace. These data agree with the findings of Kraemer et al. (29) after a 20-km race-pace run. They observed a significant decline in total work performed with the significant changes after 30 to 40 seconds for the right and left knee flexion/extension, respectively. This is quite similar to our finding of decreased function during the last one-third of the endurance task. Since it is possible that some type I muscle fibers had a significant reduction in energy stores, reductions in the latter part of the 50-repetition test may have been sensitive to this specific type of

fatigue. In contrast, Sherman et al. (31) found a marked deficit in exercise capacity for the knee extensors up to 7 days postmarathon. Such findings from a very long distance race indicate that the demands of a marathon are quite different in both acute physiological stress and recovery processes when compared to a 10-km race. Thus any fatigue indicators must be specific to the race distance (3, 14, 16, 18–20).

Force plate analysis of the maximal effort countermovement jump demonstrated that the 10-km race had a significant effect on the ability of the body to produce force in a closed-chain movement. A significant decrease was observed in the peak jump force from the prerace to immediately postrace and 48-hours postrace tests. This may indicate a compromised changeover between the concentric and eccentric muscle actions in the countermovement vertical jumping mechanics. The rate of force development (measured by the time to peak jump force) also demonstrated a significant decrease immediately postrace. No significant changes were found in the peak jump power at any time following the race. These data are consistent with the isokinetic data, which also indicates that the high threshold motor units required for this type of high power production were not affected by the 10-km race. Also it might be extrapolated that the calf musculature was not dramatically affected by the race (i.e., closed kinetic chain power measurements would be expected to be reduced if calf musculature had reduced force production capabilities).

In summary, the finding of a significant decrease in peak torque at $30°\cdot s^{-1}$ for the flexion movement after 48 hours of recovery represents a decrease in muscle function. The lack of significant changes at 180° and $300°\cdot s^{-1}$ movement speeds shows that there were no serious decrements to the fast-twitch motor units. Results also indicated a significant decrease in the total work done during the last one-third (17 repetitions) of the endurance test in both the flexion and extension movements. These data demonstrate a decreased ability for the quadriceps and hamstrings to perform prolonged exercise (50 repetitions) after a 10-km race. Fatigue in slow-twitch muscle fibers, which would be heavily recruited during an endurance event such as the 10-km race, is the most likely reason for a decrease in muscle function.

Practical Applications

No prior studies have evaluated closed kinetic chain total body power production following distance running. Furthermore, the importance of such data to actual subsequent race performance remains unclear and requires further direct study. However, the loss of any physical capability from baseline rested conditions indicates a reduced physiological status. This may indicate a reduction in the maximal recruitment of motor units for power performance related to ''kick'' demands or hill-running ability for some races. With the common practice of heats in various competitions (e.g., championship meets), the results of this study demonstrate a potential decrement in the hamstring muscle group may be present when near-maximal qualifying heats are run by competitors trying to make the finals. Thus it might be speculated that some type of advantage may be afforded to the higher-caliber runners who can run a race at a significantly slower pace during preliminary heats prior to the finals (which are run 48 hours later). Future studies need to directly evaluate the actual effects of distance-specific race fatigue on a subsequent race performances. However, these data from this investigation are for the most part consistent with and give support to the rule mandating at least 48 hours rest prior to finals for the 10-km races.

References

1. Abernethy, P.J., R. Thayer, and A.W. Taylor. Acute and chronic responses of skeletal muscle to endurance and sprint exercise. *Sports Med.* 10(6):365–389. 1990.
2. Adlercreutz, H., M. Harkonen, K. Kuopasalmi, H. Naveri, H. Huhtaniemi, H. Tikkanaen, K. Remes, A. Dessypris, and J. Karvonen. Effect of training on plasma anabolic and catabolic steroid hormones and their response during physical exercise. *Int. J. Sports Med.* 7:27–28. 1986.
3. Asmussen, E. Muscle fatigue. *Med. Sci. Sports Exerc.* 11(3):313–321. 1979.
4. Biodex System 2. *Operations Manual.* Shirley, NY: Biodex, 1992.
5. Borg, G. *Physical Performance and Perceived Exertion.* Sweden: Gleerup, 1962.
6. Borg, G. Perceived exertion: A note on history on methods. *Med. Sci. Sports* 5:90–93. 1973.
7. Burke, R.E., and V.R. Edgerton. Motor unit properties and selective involvement in movement. In: *Exercise and Sport Science Reviews.* J.H. Wilmore, ed. New York: Academic Press, 1975. pp. 31–81.
8. Cooke, R., and E. Pate. The inhibition of muscle contraction by the products of ATP hydrolysis. In: *Biochemistry of Exercise VII.* A. Taylor, P. Gollnick, H. Green, D. Ianuzzo, E.G. Noble, G. Metivier, and J.R. Sutton, eds. Champaign, IL: Human Kinetics, 1990. pp. 59–72.
9. Costill, D.L. The relationship between selected physiological variables and distance running performance. *J. Sports Med. Phys. Fitness* 7:61–66. 1967.
10. Costill, D.L. Metabolic responses during distance running. *J. Appl. Physiol.* 28(3):251–255. 1970.
11. Costill, D.L. *Inside Running: Basics of Sports Physiology.* Indianapolis: Benchmark Press, 1986.
12. Costill, D.L., and E.L. Fox. Energetics of marathon running. *Med. Sci. Sports* 7:81–86. 1969.
13. Costill, D.L., P.D. Gollnick, E.D. Jansson, B. Saltin, and E.M. Stein. Glycogen depletion pattern in human muscle fibers during distance running. *Acta Physiol. Scand.* 89:375–383. 1973.
14. Crockett, J.L., V.R. Edgerton, S.R. Max, and R.J. Barnard. The neuromuscular junction in response to endurance training. *Exp. Neurol.* 51:201–215. 1976.
15. Daniels, J., R. Fitts, and G. Sheenan. *Conditioning for Distance Runners,* New York: John Wiley and Sons, 1978.
16. Doherty, K. *Track and Field Omnibook.* Swarthmore, PA: Tafmop Publishers, 1985.

17. Dudley, G.A., R.T. Harris, M.R. Duvoisin, B.M. Hather, and P. Buchanan. Effect of voluntary vs. artificial activation on the relationship of muscle torque to speed. *J. Appl. Physiol.* 69:2215–2221. 1990.
18. Fitts, R.H., and J.O. Holloszy. Contractile properties of rat soleus muscle: Effects of training and fatigue. *Am. J. Physiol.* 233:C86–C91. 1977.
19. Ganong, W.F. *Review of Medical Physiology,* 16th ed. Norwalk, CT: Appleton and Lange, 1993.
20. Gollnick, P.B., R.B. Armstrong, B. Saltin, C.W. Saubert, W.L. Sembrowich, and R.E. Shepard. Effect of training on enzyme activity and fiber composition of human skeletal muscle. *J. Appl. Physiol.* 35(1):107–111. 1973.
21. Henneman, E. Relation between size of neurons and their susceptibility to discharge. *Science* 126:1355–1357. 1957.
22. Henneman, E., and C.B. Olson. Relations between structure and function in the design of skeletal muscles. *J. Neurophysiol.* 28:581–598. 1965.
23. Holloszy, J.O., and E.F. Coyle. Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. *J. Appl. Physiol. Respir. Environ. Exerc. Physiol.* 56(5):831–838. 1985.
24. Hoppeler, H., P. Luthi, H. Claassen, E.R. Weibel, and H. Howald. The ultrastructure of the normal human skeletal muscle: A morphometric analysis on untrained men, women, and well-trained orienteers. *Plugers Archiv. Fur die gesamte Physiolog.* 355:217–232. 1973.
25. Houmard, J.A., D.L. Costill, J.B. Mitchell, S.H. Park, and T.C. Chenier. The role of anaerobic ability in middle distance running performance. *Eur. J. Appl. Physiol.* 62:50–53. 1991.
26. Houmard, J.A., B.K. Scott, C.L. Justice, and T.C. Chenier. The effects of taper on performance in distance runners. *Med. Sci. Sports Exerc.* 26(5):625–631. 1995.
27. Jackson, A.S., and M.L. Pollock. Practical assessment of body composition. *Phys. Sportsmed.* 13(5):76–85. 1985.
28. Jacobs, I., P. Kaiser, and P. Tesch. Muscle strength and fatigue after selective glycogen and physical performance. *Eur. J. Appl. Physiol.* 56:57–53. 1981.
29. Kraemer, W.J., S.J. Fleck, and B.J. Noble. Muscle strength and endurance following long distance treadmill running. *J. Hum. Muscle Perform.* 1(3):32–39. 1991.
30. Kraemer, W.J., J.F. Patton, S.E. Gordon, E.A. Harman, M.R. Deschenes, K. Reynolds, R.U. Newton, N.T. Triplett, and J.E. Dziados. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J. Appl. Physiol.* 78(3):976–989. 1995.
31. Sherman, W.M., L.E. Armstrong, T.M. Murray, F.C. Hagerman, D.L. Costill, R.C. Staron, and J.L. Ivy. Effect of a 52.2-km footrace and subsequent rest or exercise on muscular strength and exercise capacity. *J. Appl. Physiol. Respir. Environ. Exerc. Physiol.* 57(6):1668–1673. 1985.
32. Thorstensson, A., and J. Karlsson. Fatigability and fibre composition of human skeletal muscle. *Acta. Physiol. Scand.* 98: 318–322. 1976.

Acknowledgments

We would like to thank all of the athletes who participated in this project. In addition we would like to thank all of the laboratory staff who helped with the project and logistics of testing the athletes.

Address correspondence to William J. Kraemer, PhD, kraemer@uconnvm.uconn.edu.