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The Relationships Between Local Muscular Endurance and Kinematic Changes During a Run to Exhaustion at $v\dot{V}O_2max$

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Abstract. Hayes, P.R., S.J. Bowen, and E.J. Davies. The relationships between local muscular endurance and kinematic changes during a run to exhaustion at $v\dot{V}O_2$max. *J. Strength Cond. Res. 18(4):000–000. 2004.*—A recent study suggested that runners who maintain a stable running style are able to run for longer at $v\dot{V}O_2$max velocity ($v\dot{V}O_2$max). This may be because of the capacity of various muscle groups to maintain their functions despite the onset of fatigue. The purpose of this study was to examine the relationship between local muscular endurance of both the hip and knee extensor and flexor muscle groups and the kinematic changes during a run to exhaustion at $v\dot{V}O_2$max. Six subelite runners (age 24.2 ± 4.2) participated in this study; they were considered as a homogeneous group based upon their $v\dot{V}O_2$max scores (coeffeicient of variation = 3.9%). They performed an incremental protocol to determine $v\dot{V}O_2$max, a series of isokinetic tests to determine the local muscular endurance of both knee and hip flexors and extensors, and a run to exhaustion at $v\dot{V}O_2$max. The change in kinematic variables between the beginning and the end of the run were correlated with the measures of muscular endurance. Several statistically significant negative correlations emerged between the change in stride length and concentric hip extension (HE_{con}), $r = -0.934$; eccentric hip extension (HE_{ecc}), $r = -0.818$; eccentric knee flexion (KF_{ecc}), $r = -0.957$; and change in maximum hip extension (Δ max HE), $r = -0.857$; and Δ max HE with HE_{con}, $r = -0.846$. We concluded that the local muscular endurance of both HE_{con} and KF_{ecc} are important in maintaining a stable running style.

Key Words. fatigue, strength, biomechanics, running, $v\dot{V}O_2$max

Introduction

Most analyses of middle and long distance running events focus on the metabolic determinants of performance (30, 35). Nicol et al. (22, 23), however, have suggested that there may be a neuromuscular component to fatigue in these events. Several studies (11, 12, 28, 34) have shown changes in biomechanics throughout these activities. Some of these studies have focused upon races (11) or on competitive events simulated on a treadmill (28, 34). Gazeau et al. (12) examined a treadmill run to exhaustion at the velocity at $\dot{V}O_2$max ($v\dot{V}O_2$max). They found changes in a variety of kinematic variables during the second half of the run. Gazeau et al. (12) found that those runners exhibiting the most stable running styles were able to run for longest.

Resistance training has been shown to delay fatigue in high-intensity aerobic events. Hickson et al. (14) added a weight training program to well-trained endurance athletes. After 8 weeks, they found an increase in time to exhaustion at $v\dot{V}O_2$max despite no change in $\dot{V}O_2$max. Paavolainen et al. (27) split a group of well-trained endurance runners into 2 subgroups. One group continued their normal program of running. The other group reduced their running and introduced a combination of plyometric and low resistance weight training. Improvements in 5-km time were found for the resistance trained group despite no change in the physiological parameters recorded. It was suggested that the mechanisms through which these improvements arose could be attributed to neural adaptations.

Noakes (26) argued that muscular factors have a role to play in high intensity endurance performance. Gazeau et al. (12) postulated that the ability of the knee flexors to maintain their braking role despite the onset of fatigue was a key factor in maintaining stride mechanics. It is assumed that this requires local muscular endurance in the knee flexors. The purpose of this study was to examine the relationship between local muscular endurance of both the hip and knee extensor and flexor muscle groups and the biomechanical changes during a run to exhaustion at $v\dot{V}O_2$max. We hypothesized that there would be strong negative correlations between local muscular endurance and the changes in a variety of kinematic variables.

Methods

Experimental Approach to the Problem

The aim of the study was to examine the extent of any relationships between local muscular endurance and kinematic changes during a run to exhaustion. We reproduced the method of Gazeau et al. (12) to analyze the kinematic changes during a run to exhaustion. The hypothesis was tested by correlating performance during a series of isokinetic tasks designed to assess local muscular endurance with the change in various kinematic variables measured at the beginning and end of the run.

Subjects

Six subelite male middle distance runners who had been training for more than 2 years and competed regularly participated in the study. The group consisted of three 800-m runners, whose personal best (PB; mean (± range)) was 112.1 (2.1) seconds; two 1,500-m runners, whose PB was 234.0 (8.0) seconds; and one 3,000-m runner, whose PB was 510 seconds. Their mean (± *SD*) age, height, weight, $\dot{V}O_2$max, and $v\dot{V}O_2$max were 24.2 (4.2) years, 1.81 (0.03) m, 73.4 (4.4) kg, 61.7 (5.6) $ml \cdot kg^{-1} \cdot min^{-1}$, and 20.6 (0.8) $km \cdot h^{-1}$, respectively. The sample was deemed to be homogenous based on their $v\dot{V}O_2$max data (coefficient of variation = 3.9%). The study took place towards the end of the basic preparation phase of each runner. Four of the participants regularly used resistance training, with 3 using plyometrics and core stability work. All participants provided written informed consent. The study was approved by the Division of Sport Sciences, Northumbria University Ethics Committee.

Procedure

The participants completed 3 tests: an incremental protocol to determine each participant's velocity at $v\dot{V}O_2max$, a run to exhaustion at $v\dot{V}O_2max$, and isokinetic measurements of local muscular endurance.

Determination of $v\dot{V}O_2max$

Velocity at $\dot{V}O_2max$ was measured using the protocol of Lacour et al. (18). The initial treadmill (Woodway ELG2, Waukesha, WI) velocity was 10.3 $km \cdot h^{-1}$ (0% gradient); velocity was increased by 1.5 $km \cdot h^{-1}$ every 4 minutes until volitional exhaustion. The treadmill velocity was calibrated by timing 20 revolutions of the belt 3 times during each stage. Expired gases were collected during the last 90 seconds of each stage using a Cardio-Pulmonary Exercise System (Cardio-Kinetics CP-X, Medgraphics Corporation, St. Paul, MN). The system was calibrated prior to each test according to the manufacturer's instructions.

Local Muscular Endurance Tests

All tests were conducted using a Cybex Norm dynamometer (Phoenix Healthcare, Nottingham, UK), which was calibrated prior to each test according to the manufacturer's instructions. At least 48 hours prior to testing, all subjects completed a familiarization program. The local muscular endurance task consisted of 30 maximal contractions. These were performed at $180° \cdot s^{-1}$ for the knee extensors and flexors, and hip extensors and flexors, in that sequence. The number of repetitions and velocity of movement during the isokinetic tasks were based upon tests previously used to assess national level middle distance runners (16).

Prior to the isokinetic tests, participants ran for 10 minutes at a self-selected speed. This was followed by 3 submaximal and then 3 maximal efforts on the Cybex at the test velocity. Great care was taken in the alignment of the joint axis of rotation with the dynamometer. The participant was restrained using the standard Cybex equipment, except during hip extension (HE) and hip flexion (HF); during these tests the hip strap was not used. Reciprocal muscle groups were tested using eccentric muscle actions immediately followed by concentric muscle actions to mimic the stretch-shortening cycle as far as possible. Six minutes of recovery time was given between reciprocal muscle groups and different joints. Subjects were encouraged to take active recovery.

Run to Exhaustion at vVO_2max

Following a 10-minute warm-up at 60% $v\dot{V}O_2max$ (4), subjects completed a run to exhaustion at $v\dot{V}O_2max$. The subjects stood astride the belt while the speed was increased to the test speed. When the speed reached the test velocity, the subject lowered himself onto the treadmill. The test was deemed to have begun when the subject released his grip on the hand rails. The time taken to reach exhaustion (t_{lim}) was recorded.

TABLE 1. Correlations between physiological variables and t_{lim}.

$t_{lim} - \dot{V}O_2max$	−0.343
$t_{lim} - v\dot{V}O_2max$	0.102

Biomechanical Analysis

Each run was filmed continuously at 50Hz from a distance of 7 m. Twenty points representing 18 body landmarks and 2 reference measures were obtained from each frame. Each frame was digitized (Peak Motus software—Time Base Correct FA-310P, Peak Performance Technologies, Centennial, CO). The digitizing was conducted over 3 consecutive strides with mean values taken. Two segments of the run were analyzed. The first segment was from the first right foot strike 20 seconds after the start of the run. The second segment was the first right foot strike approximately 8 seconds prior to the end of the run. Individual models were developed for each subject using the regression equations of Clauser et al. (10) to determine segmental mass. Before analyzing the digitized data, data were smoothed and filtered to remove random noise; the cutoff was set at 6 Hz. The reliability of the digitizing was determined by digitizing one subject twice. Hetroscedasticity was checked and then limits of agreement were calculated. The LOA (bias ± 95% confidence interval) for hip, knee and ankle were −0.6 ± 8.4°, −0.4 ± 8.9°, and 0.1 ± 7.9°.

Statistical Analyses

Because of the small sample size, prior to the statistical analysis each variable was checked for normal distribution using the Shapiro-Wilk test. All of the variables were found to be normally distributed. The descriptive statistics are represented as mean (*SD*). Dependent t-tests were used to assess the differences in the kinematic variables between the beginning and the end of the run to exhaustion. The relationships between local muscular endurance and the change in the kinematic variables were determined by using a Pearson correlation coefficient. The absolute differences between the beginning and end kinematic measures were calculated and then correlated with the total work done scores from the various isokinetic tests. Further relationships between the work done during the isokinetic tests and other physiological variables ($\dot{V}O_2max$, $v\dot{V}O_2max$, and t_{lim}) were also determined. Statistical significance was set at $p \leq 0.05$. All statistical analyses were conducted using SPSS (version 10, SPSS, Inc., Chicago, IL).

RESULTS

Run to Exhaustion

The mean time to exhaustion (*SD*) was 419.2 (80.8) seconds and the mean distance covered was 2,396 (485.7) m. The correlations between t_{lim} and both $\dot{V}O_2max$ and $v\dot{V}O_2max$ (Table 1) are weak and nonsignificant.

Isokinetic Parameters

There was considerable interindividual differences for the measures of local muscular endurance. The mean (*SD*) values for concentric hip extension (HE_{con}), eccentric hip extension (HE_{ecc}), and eccentric knee flexion (KF_{ecc}) were 3,653 (1,864), 6,512 (2,134), and 5,044 (1,774) J, respectively.

TABLE 2. Hip and knee angles.

	Onset	End
Hip RoM (deg)	62.2 (5.9)	61.8 (4.2)
MKE (fp) (deg)	172.3 (5.1)	168.7 (5.6)
MKE (bp) (deg)	166.7 (3.7)	166.0 (3.3)
MKF swing (deg)	140.3 (6.3)	138.3 (4.8)
MKF support (deg)	61.0 (7.3)	59.7 (12.3)

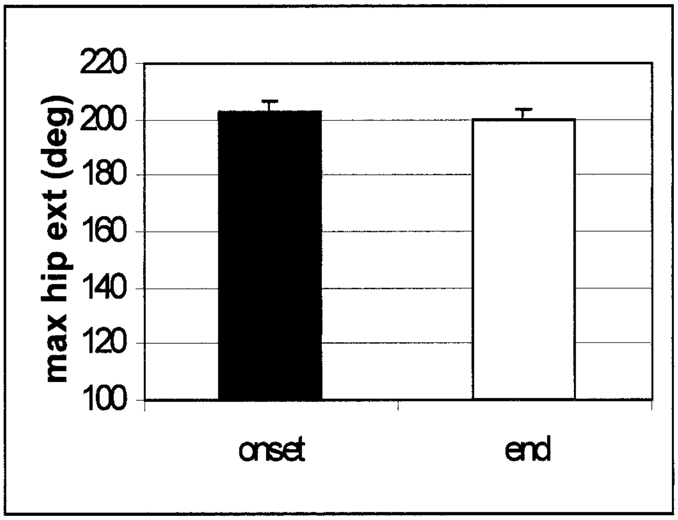

FIGURE 1. Maximum hip extension.

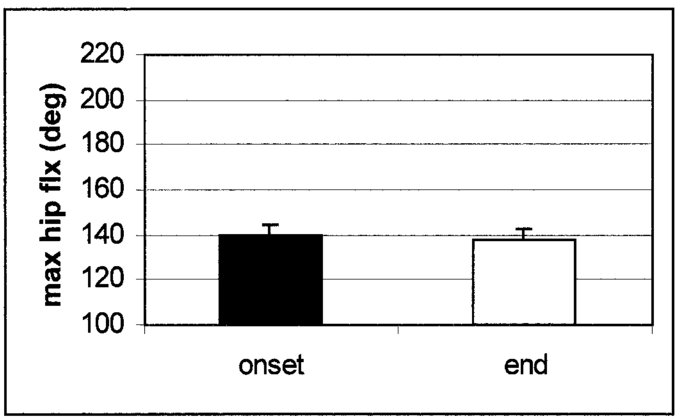

FIGURE 2. Maximum hip flexion.

Kinematics

The hip and knee angles from the beginning and end of the t_{lim} run are displayed in Table 2. There were small, nonsignificant changes in a number of knee and hip angles at various phases of the gait cycle over the course of the t_{lim} run (Table 2). The hip range of motion also remained unchanged throughout the run. Figures 1 and 2 provide a comparison of HE and HF at the onset and end of the t_{lim} run.

An analysis of stride characteristics (Table 3) revealed no significant differences in stride length, stride frequency, or support or nonsupport times. The slight changes that exist in stride frequency were partially compensated for by a shorter stride length and shorter nonsupport time towards the latter stages of the run.

TABLE 3. Stride characteristics.

	Beginning	End
Step frequency (Hz)	2.88 (0.19)	2.94 (0.17)
Stride length (m)	3.88 (0.25)	3.85 (0.23)
Support time (ms)	180 (20)	181 (10)
Non-support time (ms)	170 (20)	160 (20)

TABLE 4. Correlations between muscular strength endurance and kinematic changes.

Δ max HE and Δ SL	−0.857*
Δ max HE and HE_{con}	−0.646*
Δ SL and HE_{con}	−0.934*
Δ SL and HE_{ecc}	−0.818*
Δ SL and KF_{ecc}	−0.957*
Δ max HF and HF_{con}	−0.777
Δ max HF and HF_{ecc}	−0.809

* $p < 0.05$.

† Δ max HE = change in maximum hip extension; Δ SL = change in stride length; HE_{con} = concentric hip extension; HE_{ecc} = eccentric hip extension; KF_{ecc} = eccentric knee flexion; Δ max HF = change in maximum hip flexion.

Relationships With Local Muscular Endurance

Table 4 shows the relationships between the change in various kinematic variables over the course of the run with the time to exhaustion. The change in stride length (Δ SL) demonstrated a weak relationship with t_{lim} ($r = 0.440$; $p > 0.05$).

A number of strong significant negative correlations exist between some of the various measures of local muscular endurance and Δ SL. The change in maximum hip extension also had a strong negative correlation ($p < 0.05$) with the local muscular endurance of hip extensors during concentric muscle actions.

DISCUSSION

It has previously been shown that kinematic changes occur between the beginning and end of a run to exhaustion at $v\dot{V}O_2$max (12). The purpose of this study was to examine the relationship between kinematic changes and the local muscular endurance of the extensors and flexors of the hip and knee. We hypothesized that athletes with better local muscular endurance would exhibit smaller changes in the kinematic variables observed. The strong negative relationships we found between measures of local muscular endurance and the kinematic changes support our hypothesis.

The kinematic data for HE and HF were similar to values reported in previous studies. The range of movement (RoM) at the hip is also in accordance with previous studies. Our values are similar or slightly larger than those of Williams et al. (34), Miller (19), and Milliron and Cavanagh (20), although smaller than those of Cavanagh et al. (9) and Wank et al. (31). Nilsson et al. (25) found that HF, and therefore RoM, increased as velocity increased. The velocity within our study was slower than the studies of both Cavanagh and Wank while faster than the other studies. For maximal knee extension, in both the front and the back phases, our values are similar to Gazeau et al. (12). Similarly, for knee flexion (KF), during both the support and the swing phases, we found comparable values to Williams et al. (34). Not all of these studies used the same method when analyzing each variable. During our analysis, when we compared the method we employed with that of the original paper, we obtained similar findings.

Most of the significant relationships found within this study are those between Δ SL and measures of local muscular endurance. Other studies have reported inconsistent findings regarding changes in stride length during a run to exhaustion. Elliott and Roberts (11) found a reduction in stride length during a 3,000-m time trial on a running track. In contrast, Siler and Martin (28) and Gazeau et al. (12) found increases in stride length during a treadmill run to exhaustion at a 10-km race pace and $v\dot{V}O_2$max, respectively. Williams et al. (34) found increases in stride length during treadmill running at a 5-km pace and decreases in the same subjects during competitive track running. These differences with mode of running are compounded by large between-subject variation (28). In the current study, there was no significant difference ($p > 0.05$) between the stride length at the beginning and end of the run (3.88 ± 0.25 m vs. 3.85 ± 0.25 m). The lack of significant change has, however, masked considerable interindividual variability. In this study, 3 subjects had a reduced stride length, 2 had an increased stride length, and the other remained unchanged.

In this study, change in stride length (Δ SL) had a very strong negative correlation with local muscular endurance of the hip extensors, both concentrically and eccentrically. Both the gluteus maximus and the hamstrings contract eccentrically during the late swing phase to decelerate the thigh and control knee extension. They then contract concentrically during the early part of the stance phase, allowing the hip to drive the body over the supporting foot, which provides propulsion (21). The hamstrings are biarticular, acting as both hip extensors and knee flexors. This would explain the strong negative relationships of eccentric knee flexion (KF_{ecc}) and HE_{ecc} with stride length. Most of the eccentric work by the hamstrings is performed during knee extension; hence, there is a stronger relationship between KF_{ecc} and Δ SL than between HE_{ecc} and Δ SL. In this respect it is thought that the strong relationship between Δ SL and HE_{ecc} is possibly specious. This relationship could be caused by the activity of the hamstring group during the isokinetic assessment of HE and KF.

The importance of the hamstring group found in this study is consistent with the findings of Sloniger et al. (29). They reported that the main muscle groups activated during level treadmill running at 115% peak $\dot{V}O_2$ were the hamstrings and gracilis, both knee flexors. Furthermore, they found that the patterns of recruitment did not exactly match the intensity of muscle use. The most intensely used muscle groups were the gluteal group, followed by the hamstrings. This heavy usage of the gluteals is consistent with the strong correlation between HE_{con} and Δ SL observed in our study. Those subjects who were best able to maintain HE_{con} demonstrated the smallest Δ SL. Presumably, the ability to generate the required force delayed any reduction in stride length. Sloniger and colleagues (29) found that not all of the muscle groups were fully activated. Moreover, they postulated that there is a limit to which additional muscle mass can be utilized to produce force and energy. As these intensely used muscle groups become fatigued and their force-producing capabilities decline, it is likely that running speed will decrease, because additional muscle mass cannot be recruited to compensate.

The relationship between KF_{ecc} and Δ SL is in accordance with the work of Gazeau et al. (12). They postulated that the capacity of the knee flexors to maintain a constant braking role was important in maintaining stride length and hence running speed at $v\dot{V}O_2$max. Further support for this can be identified from the work of Jacobs et al. (15), who suggested that biarticular leg muscles were important for the distribution of joint moments and work produced at the joints during running, rather than for force generation. Local muscular endurance of the hamstrings would therefore appear to be important in decelerating the thigh and controlling the angular momentum transferred to the shank during the swing phase and the maintenance of stride length.

At foot strike and through the early stages of the stance phase, the quadriceps reach their peak activation (25). We were, however, unable to find any significant relationships between eccentric hip flexion, concentric hip flexion, concentric knee extension, or eccentric knee extension and the kinematic variables studied. Sloniger et al. (29) found the vastus group, the rectus femoris and the iliopsoas, to be the least-activated leg muscles during treadmill running to exhaustion. Moreover, they found the rectus femoris to be the least intensely used muscle of those activated. This may account for our not having found significant relationships between these variables.

Nicol et al. (23) found that as fatigue progressed during a marathon there was an increase in the duration of the push-off phase. This is supported by Gazeau et al. (12), who found an increase in support time towards the end of a run to exhaustion at $v\dot{V}O_2$max. The increase in support time may be due, in part, to the inability of the HE_{con} to continue to generate force at the required rate as fatigue develops. Given the constant running speed, and therefore constant power output, in the current study, it is proposed that local muscular endurance of the HE_{con} is an important factor in delaying fatigue and sustaining a given power output. Belli et al. (3) agreed that the concentric hamstring activity was essential for producing the power at the hip that is vital for high velocity running.

HE_{con}, in addition to being negatively related to changes in stride length, has a strong negative relationship to the change in maximal HE angle (MHE). This implies that those who were unable to continue to extend at the hip during the stance phase failed to sustain the required force generation. It is possible that this reduction in force could decrease stride length. The strong positive relationship between Δ SL and Δ MHE tends to support the importance of local muscular endurance of HE_{con} in maintaining stride length.

During repeated submaximal stretch shortening cycle (SSC) activity, there is reduced contractile performance (22–24). To some extent, this may be offset by enhanced neural input to the muscle (2, 13). Golhoffer et al. (13) found an increased total neuronal input after a repeated submaximal SSC task. They suggested that increase in neuronal activity was an attempt by the neuromuscular system to compensate for the reduction in contractile function through the regulation of muscle stiffness. Golhoffer and colleagues postulated several possible mechanisms for the loss of contractile function. First, it could be caused by changes within the intracellular$_i$ environment. They suggested that Ca^{2+} transport and acidosis, which either independently or concurrently, could impair cross-bridge force generation. Blood lactate was not recorded in the present study; however, Billat et al. (5, 6) found values of approximately 9 mmol·l^{-1} after a run at the same intensity as this study.

Alternative mechanisms proposed include an increase in the coupling time between eccentric and concentric phases of the SSC (13). Any increase in the coupling time of the eccentric and concentric phases would result in the dissipation of energy as heat rather than its use in the concentric contraction (7). Nicol (22) found a greater KF angle at foot strike with fatigue, which may reflect the change in muscle stiffness characteristics with fatigue. It has been suggested that this is caused by a reduction in the muscles' ability to absorb impact loads, with a subsequent loss of muscle recoil characteristics (17). Further studies are required to determine whether local muscular endurance can delay the changes in muscle stiffness characteristics.

The present study did not measure SSC capability of the various muscle groups. It is, however, tempting to speculate that greater local muscular endurance of KF_{ecc} would delay any decline in SSC function. During the eccentric phase of a SSC, the series elastic component of the muscle is stretched with the stored energy used in the subsequent concentric contraction (8). In such circumstances KE_{ecc} would also be expected to correlate highly with other kinematic variables. This correlation was not supported by our findings. The nonsignificant correlation of the KE_{ecc} with kinematic variables could be caused by the use of an isokinetic dynamometer rather than the loading characteristics during running. During the running gait, the eccentric phase is somewhat shorter than that experienced during the isokinetic assessment of KE_{ecc}. This would increase the coupling time of the eccentric and concentric phases, with the subsequent loss of stored energy. In a review of isokinetic testing, Abernethy et al. (1) highlighted the variability within the literature regarding the ecological validity of isokinetic assessment. It would be interesting for future studies to examine the relationship between the performance of a SSC endurance task, similar to that of Nicol et al. (22), and the change in kinematics.

This study, in common with most other studies, employed treadmill running. It is assumed in most studies that the results are transferable to overground running. Wank et al. (31) compared kinematics and EMG activity during treadmill and overground running. The fastest velocity they employed is similar to the speed of the runners in the current study. They found that, during treadmill running, there was greater activity of the bicep femoris, and that this activity lasted longer during ground contact and the first part of the swing phase. This was attributed to a greater forward trunk lean. It is possible that this may artificially strengthen the relationships of the HE and KF with the kinematic changes. At foot strike the KEs contract eccentrically, operating as "shock absorbers". Given the importance of the role of the KEs, it is surprising that this study failed to find a strong relationship between these muscle groups and the kinematic changes. During treadmill running, Wank and colleagues (31) found the activity of the vastus lateralis to be reduced during ground contact. This would reduce the role of KE_{ecc}, and would perhaps assist in explaining the nonsignificant correlations for KE_{ecc}. The increase in trunk forward lean would also presumably weaken the relationships of HF_{con} with other kinematic variables. This is supported by the poor relationship with KF_{con}.

Westblad et al. (32) found that the eccentric local muscular endurance of the knee flexors in elite middle distance runners correlated with running economy. They measured local muscular endurance during 100 contractions at 90°·sec^{-1}. This study examined kinematic changes rather than running economy, finding weaker relationships with KE_{ecc}. We, however, used 45 contractions at 180°·sec^{-1}. It is not possible to determine whether conducting more repetitions would affect the relationships identified. The differing exercise intensities and treadmill gradients employed by the 2 studies further compound the difficulties of any meaningful comparison. Both Westblad et al. and the present study have found strong relationships between local muscular endurance and parameters that influence running performance. To establish the cause-effect nature of the relationship between local muscular endurance and running kinematics, future studies should examine the effects of muscular strength endurance training upon changes in kinematics.

This study has found a number of strong, significant, negative correlations between the local muscular endurance of various muscle groups and the kinematic changes that occur during the latter stages of a run to exhaustion. The strongest of these relationships was between KF_{ecc} and Δ SL. We propose that the local muscular endurance of the hip extensors and knee flexors, in particular during eccentric work, are important in preventing or delaying these kinematic changes associated with fatigue during high-intensity endurance running.

Practical Applications

The main finding from this study is the relationship between local muscular endurance of the hip extensors and knee flexors with changes in running mechanics. This agrees with Gazeau et al. (12), who suggested that the ability of the knee flexors to maintain a constant braking role despite the onset of fatigue was critical to maintaining stride mechanics. The practical implication of this is that coaches and athletes need to consider developing local muscular endurance of both the knee flexors and the hip extensors. This will primarily involve developing the athlete's hamstrings. The strongest relationship was between the KF_{ecc} and Δ SL. This would suggest that eccentric muscle actions of the hamstrings should be included in the overall training program of middle-distance athletes.

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