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Research article

Kinematic changes during a marathon for fast and slow runners

Maggie Chan-Roper [1], Iain Hunter [1], Joseph W. Myrer [1] Dennis L. Eggett [2] and Matthew K. Seeley [1] ✉
[1] Department of Exercise Sciences and [2] Department of Statistics Brigham Young University, USA

Abstract
The purpose of this study was to describe kinematic changes that occur during an actual marathon. We hypothesized that (1) certain running kinematic measures would change between kilometres 8 and 40 (miles 5 and 25) of a marathon and (2) fast runners would demonstrate smaller changes than slow runners. Subjects (n = 179) were selected according to finish time (Range = 2:20:47 to 5:30:10). Two high-speed cameras were used to measure sagittal-plane kinematics at kilometres 8 and 40 of the marathon. The dependent variables were stride length, contact time, peak knee flexion during support and swing, and peak hip flexion and extension during swing. Two-tailed paired t-tests were used to compare dependent variables between kilometres 8 and 40 for all subjects, and regression analyses were used to determine whether faster runners exhibited smaller changes (between miles 5 and 25) than slower runners. For all runners, every dependent variable changed significantly between kilometres 8 and 40 ($p < 0.001$). Stride length increased 1.3%, contact time increased 13.1%, peak knee flexion during support decreased 3.2%, and peak hip extension, knee flexion, and hip flexion during swing decreased 27.9%, increased 4.3%, and increased 7.4%, respectively ($p < 0.001$). Among these significant changes, all runners generally changed the same from kilometres 8 and 40 except that fast runners decreased peak knee flexion during support less than the slow runners ($p < 0.002$). We believe that these changes, for all runners (fast and slow), were due to fatigue. The fact that fast runners maintained knee flexion during support more consistently might be due to their condition on the race day. Strengthening of knee extensor muscles may facilitate increased knee flexion during support throughout a marathon.

Key words: Fatigue, endurance, run, biomechanics, race.

Introduction

Marathon running is becoming an increasingly popular sport. In 2001, the five most well-known marathons in the world—Boston, Chicago, Berlin, London and New York City—had a total of 121,291 finishers. In 2010, the total finishers of these marathons increased by over 43% to 173,958. Marathon running involves a challenging distance (42 km 125 m) and produces physiological changes that may alter running biomechanics during the race (Hausswirth and Lehénaff, 2001).

Kinematics and economy of prolonged running have been extensively studied. Most runners choose their stride length to optimize their running economy when running non-fatigued (Cavanagh and Williams, 1982). When running fatigued, however, decreased stride length does not affect running economy (Kyröläinen et al., 2000; Elliott and Roberts, 1980), and stride frequency decreases while oxygen uptake increases (Hunter and Smith, 2007). Contact time increases slightly as fatigue occurs (Elliott and Roberts, 1980), due to increased peak knee flexion during support (Derrick et al., 2002; Kellis and Liassou, 2009; Nicol et al., 1991). Peak knee flexion during swing also increases during fatigue (Hausswirth et al., 1997). Although peak hip flexion during swing does not change, peak hip extension during swing decreases during prolonged running (Elliott and Roberts, 1980). However, kinematic alterations when running under fatigued conditions vary among individuals (Nicol et al., 1991; Siler and Martin, 1991) and between study designs.

Although the kinematics of prolonged running has been previously studied, little is known regarding how kinematics may change during an actual marathon. To our knowledge, no one has evaluated kinematic changes between the early and late stage of an over-ground marathon. Additionally, only one group of researchers has compared kinematic changes between fast and slow runners during a prolonged run: Siler and Martin (1991) reported that kinematics for fast and slow runners change similarly during a fatiguing 10-km treadmill run. However, treadmill running in a laboratory setting likely results in kinematics that differs from over-ground racing (McKenna and Riches, 2007; Morin et al., 2009; Nigg et al., 1995; Riley et al., 2008).

The purpose of this study was to evaluate running kinematic characteristics during early and late stages of an actual marathon, for fast and slow runners. We asked two research questions: (1) Do running kinematic characteristics change over an actual marathon? and (2) Do potential kinematic changes differ between fast and slow runners? We hypothesized that certain running kinematics change from the early to late stage of an actual marathon, and that observed kinematic changes would be smaller for fast runners than slow runners.

Methods

Subjects

Subjects (n = 179) were all participants in the 2010 Salt Lake City Deseret News Marathon. Subject selection was based primarily on finish time. Subject finish times ranged from 2:20:47 to 5:30:10. We attempted to select approximately one subject per half minute (finish time). Subjects were excluded if they walked, carried a water bottle or cup, wore a backpack, or exhibited obvious limping, tripping, or falling when passing our cameras' fields of view. Selected subjects were matched using their race bib number and/or clothing between kilometres 8 and 40 (miles 5 and 25). Approval for this study was obtained from the race executive board and appropriate human subject institution review board prior to data collection.

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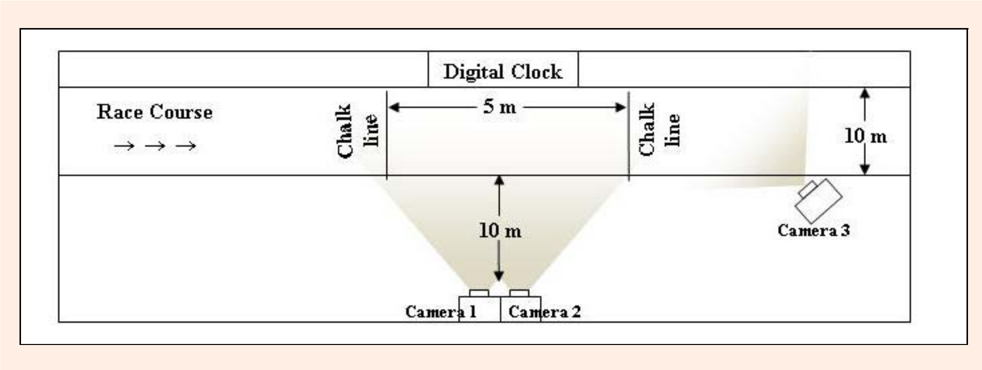

Figure 1. A schematic depicting the camera set up at kms 8 (5 mile) and 40 (25 mile).

Data collection

Three cameras were set up at kilometres 8 and 40 (Figure 1). Two high-speed digital cameras (Casio Exilim FH-100; shutter speed = 1/250 s, frame rate = 120 Hz. Cameras 1 and 2 in Figure 1) were set on tripods side by side, 10 m away from the right side of the race course, at a height of 1 meter. Only one of these cameras recorded at a time. Digital storage space limited each camera to 11.5 minutes of recording at a time. After every 11.5 minute recording, 5minutes were needed to process and download the recorded video to a computer. The second high-speed camera recorded during this 5-minute duration. Five meters of level course were measured and marked with white chalk lines (Figure 1). We ensured that these 5 meters were level using survey equipment. Fields of view for Cameras 1 and 2 were both set to video across the entirety of this 5-m length. A third camera (Canon Vixia HF200; shutter speed = 1/250 s, frame rate = 60 Hz. Camera 3 in Figure 1) was set on a tripod at a height of 1 meter, with a frontal view of the runners. This camera was used to identify and match the runners between miles 5 and 25. A digital clock was placed directly across from Cameras 1 and 2 to show the marathon time and assist with subject selection

Data Analysis

The following kinematic variables were derived from the collected video at kilometres 8 and 40 using Dartfish 5.5 software (Dartfish, Fribourg, Switzerland): (1) running speed through the aforementioned 5-meter length, (2) stride length, (3) contact time, (4) sagittal-plane knee angle throughout one gait cycle, and (5) sagittal-plane hip angle throughout one gait cycle. For the joint angles, zero degrees represented anatomical position. Hip flexion, hip extension (beyond anatomical position), and knee flexion were indicated by angles that were greater than zero (as these motions increased, the magnitude of angle also increased). The following eight dependent variables were examined at kilometres 8 and 40 for all subjects: (1) running speed, (2) stride length (SL), (3) stride frequency (SF), calculated according to the running speed and SL, (4) contact time, (5) peak knee flexion during support, (6) peak hip flexion during swing, (7) peak knee flexion during swing and (8) Peak hip extension during swing.

Statistical analyses

Related to the first research question, the influence of running from 8 km to 40 km on the dependent variables was evaluated using two-tailed paired t-tests. The dependent variables were normalized to the running speed at the corresponding mile marker and calculated as a ratio of kilometres 8 and 40. These ratios were then compared to the value of 1 using the aforementioned t-tests. A ratio that was significantly less than 1 indicated that the dependent variable decreased between kilometres 8 and 40, while a ratio that was greater than 1 indicated that the dependent variable increased between kilometres 8 and 40.

Related to the second research question, we used a mixed models regression analysis blocking on subjects, with the running speed at the corresponding mile marker as a covariate, to examine a potential interaction between average speed (across the entire marathon) and between kilometres 8 and 40 changes for the kinematic dependent variables in a non-normalized form. This procedure allowed us to determine whether fast runners altered their running kinematics differently than slow runners. Significance levels for all statistical analyses were set to 0.01, due to multiple variables and tests. Because the running speed at the corresponding mile marker had direct correlation with all the dependent variables except peak knee flexion during support, the running speed at the corresponding mile marker was not used as a covariate for peak knee flexion during support.

Results

The sample means and standard deviations for each dependent variable are presented in Table 1. It is important to remember that the values presented in Table 1 were not normalized to running speed at the corresponding mile markers. Table 2 presents ratios (km 8 to 40) of kinematic values that were normalized to running speed at the corresponding mile marker. Related to the first research question, all dependent variables changed significantly between kilometres 8 and 40 (Table 2). Stride length, contact time, peak knee flexion during swing, and peak hip flexion during swing increased between kilometres 8 and 40, while running speed, stride frequency, peak knee flexion during support and peak hip extension during swing decreased. Related to the second research question, the only kinematic variable that exhibited a significant interaction between kilometres 8 and 40 was peak knee flexion during support ($t = 3.19, p < 0.002$), which

Table 1. Mean (±standard deviations) for the kinematic variables at kilometers 8 and 40.

Kinematic variables	8 km	40 km
Running speed ($m \cdot s^{-1}$)	3.23 (.43)	2.89 (.50)
Stride length (m)	2.26 (.30	2.04 (.33)
Stride frequency (strides/s)	1.43 (.07	1.41 (.07)
Contact time (s)	.29 (.04)	.31 (.04)
Peak knee flexion during support (degree)	42.7 (4.4)	41.2 (4.8)
Peak hip extension during swing (degree)	16.4 (6.7)	13.4 (7.7)
Peak knee flexion during swing (degree)	94.1 (12.1)	87.0 (11.6)
Peak hip flexion during swing (degree)	42.0 (5.9)	39.7 (6.6)

indicated that the fast runners decreased peak knee flexion during support less than the slow runners at 40 km when compared to 8 km (Figure 2). Additionally, the regression analyses related to peak knee flexion during support were statistically significant at 8 km ($t = -6.90$, $p < 0.001$) and 25 ($t = -3.88$, $p < 0.001$); although this finding does not directly relate to our research questions, it indicates that fast runners exhibited more peak knee flexion during support than the slow runners throughout the race (Figure 2 and Table 3).

In summary, the runners demonstrated significant kinematic changes between kilometres 8 and 40 for all of the observed kinematic variables. The fast runners decreased their peak knee flexion during support significantly less than the slow runners between kilometres 8 and 40.

Discussion

The purposes of this study were to (1) evaluate potential changes in running kinematics during an actual marathon and (2) compare these potential changes between fast and slow runners. Although running kinematics has been studied extensively, this was the first observation of running kinematics during early and late stages of an actual marathon. Related to the first research question, all of the observed running kinematics changed significantly between kilometres 8 and 40 of a marathon, even after normalizing each data point to the running speed at the early and late stages of the race. Related to the second research question, fast runners exhibited smaller decreases in peak knee flexion during support than slow runners, between kilometres 8 and 40 (i.e., the fast runners more consistently maintained peak knee flexion during support throughout the race, relative to the slow runner); otherwise, the fast runners changed their running kinematics in a way that was similar to the slow runners.

For all runners, stride length increased significantly between kilometres 8 and 40 (Table 2). This finding accompanies a decreased stride frequency, similar to the findings of Hunter and Smith (2007); but contradicts the results of Elliott and Roberts (1980). We believe their study design might have contributed to these contradicting results; for example, they did not consider possible surging at the last stage (the 2900-meter mark of a 3000-meter trial) especially the mean running speed of that last stage was actually the fastest one. Therefore, we believe an optimal running economy involved an increase in stride length when fatigue onset at the late stage of a marathon in combination with other kinematic changes, discussed in the following paragraphs.

The present results regarding contact time (Table 2) concur with previously reported results (Derrick et al., 2002; Kellis and Liassou, 2009; Nicol et al., 1991). In the presence of fatigue, runners fail to fully utilize the stretch-shortening mechanism (Derrick et al., 2002), especially about the hip and knee joints. This may be related to the fact that the biceps femoris and rectus femoris are the first to fatigue during long-distance running (Hanon and Thépaut-Mathieu, 2005). This muscle fatigue results in reduced leg stiffness which in turn results in the attenuation of ground reaction forces and increased contact time (Mercer et al., 2002).

Related to the increased contact time, decreased peak knee flexion during support (Figure 2 and Table 2) could be explained by the inverse relationship between leg stiffness and energy cost of running (Dalleau at al., 1998). Because decreased peak knee flexion during support implies an increase in leg stiffness (McMahon and Cheng, 1990), the energy cost of running decreases (Dalleau at al., 1998) especially at the late stage of a marathon. The measurement of ground reaction forces during an actual marathon, although logistically difficult, could elucidate the aforementioned speculation in future studies.

Data relating to the increased peak knee flexion during swing (Table 2) at the late stage of the race when compared to the early stage of the race in this study may be best explained by the principle of angular inertia ($H = I\omega$, where H is angular momentum, I is the moment of inertia and ω is the angular momentum). Increased peak knee flexion during swing decreases the moment of inertia of the lower extremities about the hip joint and

Table 2. The means (±standard deviations) for the ratio of 40 km to 8 km of each kinematic variable. It is important to remember that these ratios involve kinematic data that were normalized to the running speed at the corresponding mile marker. This normalization process altered the direction of change, relative to the raw data that is presented in Table 1.

Kinametic variables	Ratio of km 40:8	Direction of change
Stride length	1.013 (.038) *	1.3% increase
Contact time	1.131 (.131) *	13.1% increase
Peak knee flexion during support	.968 (.095) *	3.2% decrease
Peak hip extension during swing	.721 (2.816) *	27.9% decrease
Peak knee flexion during swing	1.043 (.101)*	4.3% increase
Peak hip flexion during swing	1.074 (.183) *	7.4% increase

* Significantly ($p < 0.001$) different at 40 km when compared to 8 km.

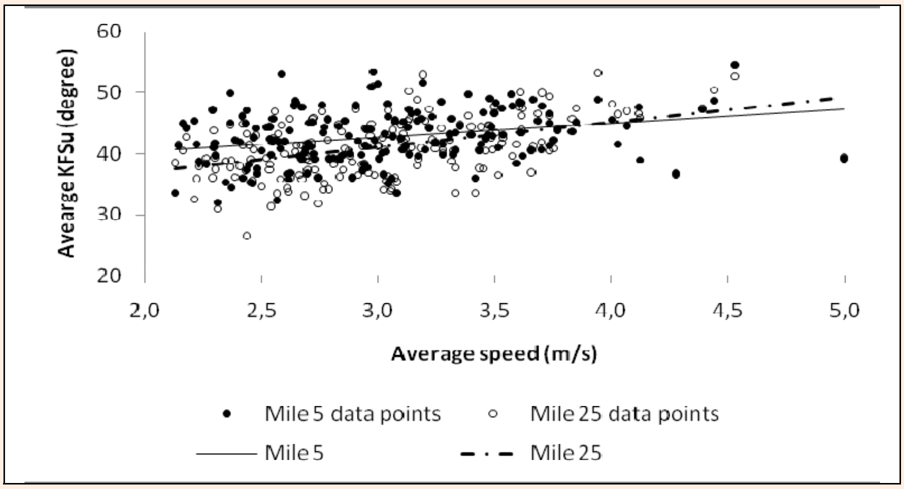

Figure 2. Sample peak knee flexion during support data points. The fast runners have significantly more peak knee flexion during support than the slow runners at both mile 5 (8 km) ($p < 0.001$) and mile 25 (40 km) ($p<0.001$). The difference between miles 5 (8 km) and 25 (40 km) was also significant, which indicated that the fast runners decreased their peak knee flexion during support significantly less than the slow runners ($p < 0.002$).

increases angular velocity (Shim et al., 2003). This increased peak knee flexion during swing supports the ease of swing phase and appears to be a more economical running attribute (Hausswirth et al., 1997).

Data in this study showed a 27.9% decrease in peak hip extension during swing and a 7.4% increase in peak hip flexion during swing (Table 2). These changes in hip kinematics could have been caused by increased trunk flexion that has been previously documented during fatigued running (Elliott and Roberts, 1980 and Hausswirth et al., 1997). Because the hip joint angles were measured in reference to the trunk position, increased trunk flexion would shift the hip measurements forward (i.e., more hip flexion and less hip extension during swing) with an overall decrease range of motion about the hip joint. Increased trunk flexion, however, provides better dynamic stability even though it may increase abnormal stress on the lower-extremity joints (Farrokhi et al., 2008) and further fatigue the lower-extremity muscles and increase the risk of injury (Hart et al., 2009).

Kinematic changes we observed between kilometres 8 and 40 may also be the result of other factors, in addition to the failure of force production among lower-extremity muscles due to fatigue (Hanon and Thépaut-Mathieu, 2005). Decreased neuromuscular activation (Nicol et al., 1991), altered energy substrate utilization, increased demands for body temperature regulation, muscle damage (Kyröläinen et al., 2000), and/or musculotendon structural changes (Tardioli, 2011) could all potentially influence kinematics during a long run. Although these issues are outside the scope of this study, they might be clarified with future research.

Related to our second research question, the present data fit with the findings of Siler and Martin (1991). All runners change their running kinematics similarly, except that the fast runners in this study decreased their peak knee flexion during support less than the slow runners between kilometres 8 and 40 (Table 3). Fast runners also exhibited significantly more peak knee flexion during support than slow runners throughout the race. We believe this peak knee flexion during support difference is best explained by the different conditions of the runners on the race day: through genetic differences or differences in training. Fast runners are likely more capable to effectively produce muscular force over a more extended period of time, relative to the slow runners. Additionally, the slow runners in our study ran for a longer period of time: the fastest and slowest subjects finished the marathon at2:20:47 and 5:30:10, respectively. In speculation, if the fast runners would have been forced to run for another 3 hours, the results from the comparisons between fast and slow runners may have been different.

The present findings imply that runners need not be overly concerned about any kinematics in order to run faster. While peak knee flexion during support was the only kinematic variable separated the fast runners from

Table 3. A regression slope of each kinematic variable at kilometers 8 and 40 and its slope difference between kilometers 8 and 40.

Kinametic variables	Slope				Slope difference
	8 km	p value	40 km	p value	(p value)
Stride length	.013	.528	.020	.340	.521
Contact time	-.005	.208	-.007	.113	.461
Peak knee flexion during support	2.299	< 0.001 *	4.085	< .001*	< .002 †
Peak hip extension during swing	.905	.480	1.024	.448	.887
Peak knee flexion during swing	2.853	.063	1.529	.341	.175
Peak hip flexion during swing	2.228	.072	.891	.449	.063

*The fast runners had significantly more peak knee flexion at support than the slow runners. † The fast runners decreased their peak knee flexion during support significantly less than the slow runners at 40 km when compared to 8 km.

the slow runners, focusing on resistance training that would increases in both muscular strength and endurance of the knee extensors may increase peak knee flexion during support and maintain a more peak knee flexion during support throughout a marathon.

There were some limitations related to this study. First, some direct lines of sight were blocked by other runners when some of the runners passed by the cameras' fields of view, especially at 8 km. Consequently, we were unable to collect some data that would have otherwise been collected, particularly for some of the fast runners. Second, using the present methods, any change of running kinematics that may have been related to an existing injury or injury acquired during the race could not be evaluated. Third, subjects might run asymmetrically between left and right lower extremities, however, only the right leg was analyzed. For future reference, setting cameras on both sides of the race course could minimize some of these limitations and increase validity.

Conclusion

In conclusion, we observed that, between kilometres 8 and 40, runners generally demonstrate increased stride length, contact time, peak hip flexion during swing, and peak knee flexion during swing, and decreased running speed, stride frequency, peak knee flexion during support and hip extension during swing. We believe that these changes were due to fatigue. In contradiction to our second hypothesis, the observed kinematics generally changed the same (between kilometres 8 and 40) for the fast and slow runners; however, the fast runners did exhibit a more consistent peak knee flexion during support throughout the race, relative to the slow runners. This may have been related more to the runners' condition on race day. Runners should focus on resistance training which would be directed toward increases in both muscular strength and endurance of knee extensors. By so doing, peak knee flexion during support should be increased and be able to be maintained longer throughout the marathon.

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Key points

- Runners changed kinematics significantly from kilometres 8 to 40 (increased stride length, contact time, peak hip flexion during swing, and peak knee flexion during swing, and decreased running speed, stride frequency, peak knee flexion during support and peak hip extension during swing).
- Fast runners demonstrated more peak knee flexion during support throughout a marathon
- Runners generally changed kinematics similarly (between kilometres 8 and 40) except that fast runners exhibited a more consistent peak knee flexion during support than slow runners.
- Resistance training that would increase both muscular strength and endurance of knee extensors may increase peak knee flexion during support and help maintain it similar to the fast runners throughout a marathon.

AUTHORS BIOGRAPHY

Maggie CHAN-ROPER
Employment
Graduate Student at Brigham Young University, USA
Degree
MSc
Research interests
Improved performance and prevention of injuries in distance running and coaching.
E-mail: mchanroper@gmail.com

Iain HUNTER
Employment
Department of Exercise Sciences, Brigham Young University.
Degree
PhD
Research interests
Distance running economy and technique of track and field events.
E-mail: iain_hunter@byu.edu

Joseph William MYRER
Employment
Department of Exercise Sciences, Brigham Young University.
Degree
PhD
Research interests
Diagnostic ultrasound (Intramuscular blood flow), topical analgesics and therapeutic modalities
E-mail: bill_myrer@byu.edu

Dennis L. EGGETT
Employment
Department of Statistics, Brigham Young University.
Degree
PhD
Research interests
Linear models, mixed models, and design of experiments
E-mail: theegg@stat.byu.edu

Matthew SEELEY
Employment
Department of Exercise Sciences, Brigham Young University.
Degree
PhD
Research interests
The biomechanics of human locomotion.
E-mail: matt_seeley@byu.edu

✉ **Matthew Seeley**
106 SFH, Brigham Young University, Provo, Utah 84602, USA