Original Article

Compensatory changes in female running mechanics during a simulated 10 km race

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ABSTRACT

During a 10 km run at race pace, changes in lower extremity mechanics have been reported in male runners however mechanical changes over 10 km in female runners is unknown. Thus we aimed to examine running mechanics in females during a simulated 10 km race on a treadmill. Nine female distance runners (age: 32.1±4.2 yrs; ht: 166.7 ± 7.4 cm; wt: 57.8 ± 7.0 kg; VO_{2max} = 3.24 ± 0.50 L/min) completed graded exercise testing (Day 1); 10km time trial (Day 2); and simulated 10km treadmill run (DAY 3; 95 % of running velocity from Day 2 time-trial). Mechanical data sampled at 120Hz using a 6-camera optoelectronic motion capture system and effort (Rating of Perceived Exertion - RPE) were measured at 50, 1450, 2950, 4450, 5950, 7450, 8950 and 9950 metres. Maximum voluntary contraction of knee extensors was measured pre-post. Seven participants decreased MVC (1-21% decrease) and RPE increased from 12 (50m) to 19 (9950m). Step frequency decreased 3 steps/min ($p<0.05$) and step length increased 3cm. Max knee extension and max knee flexion increased from 50m to 9950m and hip height was lowered over the 10km time-trial. These results indicate that whole body fatigue influences RPE and is associated with mechanical changes to maintain pace in female runners. Specifically, the combination of knee extension and knee flexion increases likely reduces limb inertia as the runner fatigues minimizing decreases in step frequency and improving step length. These results are the first to illuminate the fatigue related intrinsic coping mechanisms of female runners at race pace. **Key words:** KINEMATICS, EXERCISE FATIGUE, RUNNING PERFORMANCE, ENDURANCE ATHLETE.

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INTRODUCTION

Distance running has grown in popularity with over 19 million Americans participating in road running races in 2013 in distances from 1km to ultramarathons (Report, 2010). As with any timed competitive event individuals competing in these races are focused on completing the distance as fast as possible. However, to do this, runners must overcome accumulating fatigue (Elliot & Ackland, 1981) and while fatigue in a physiological manner is clearly defined as a loss of force production or power (Ament & Verkerke, 2009; Gerdle, Larsson, & Karlsson, 2000; Williams & Cavanagh, 1987), the ability to assess fatigue or its effects in a sport setting like running races is difficult. Some research has examined self-paced models where fatigue is defined as "the inability to complete the run any faster" but does not examine the within race/time trial changes that occur due to fatigue. Thus our understanding of the role fatigue might play in an athlete's coping strategy with accumulating fatigue and subsequent performance outcomes is limited (Winter, Gordon, & Watt, 2016). This project addresses this need for real time evaluation of within race/time trial changes in runners.

Research investigating the effects of fatigue on running has focused on male distance runners, with no significant inquiry in female athletes. This is surprising considering that women accounted for 44% of marathon participants in the United States in 2015 (Report, 2010) and the fact that gender differences as described below exist while running on a treadmill at different speeds (Barrett, Noordegraaf, & Morrison, 2008; Ferber, Davis, & Williams, 2003; Hanley & Smith, 1998). In non-fatiguing trials, Hanley & Smith, (Hanley & Smith, 1998) and Ferber et al. (Ferber et al., 2003) in running treadmill trials have shown that women are less variable than men for transverse plane rotations of the ankle, hip and knee, and sagittal rotations of the ankle at given running speeds. These differences were hypothesized to be due to structural differences between men and women including females having larger genu valgum at the knee and larger Q-angle with respect to the hip (Ferber et al., 2003). However these findings can only be applied to non-fatigued running mechanics and others (Barrett et al., 2008) have indicated that further research is needed to determine whether increases in fatigue would magnify these differences. Thus, the effect of fatigue on mechanics in female runners remains an important, but unanswered question in the sport science literature.

Research that has examined exercise induced fatigue, has found that fatigue causes a reduction in the ability to generate muscular forces in the lower limb (Gerdle et al., 2000). This inability to maintain force production is believed to influence running mechanics which in turn may influence running performance (Hinrichs, Cavanagh, & Williams, 1987; Mizrahi, Verbitsky, Isakov, & Daily, 2000; Siler & Martin, 1991). Specifically, fatigue has been shown to effect stride length and frequency and is thought to contribute to changes in the angles of the knee and hip as well as increase vertical displacement of the runner's center of mass in male runners (CoM) (Hinrichs et al., 1987; Mizrahi et al., 2000; Siler & Martin, 1991). However direct assessment of mechanics in the lower limb at race pace as fatigue accumulates is not well understood in male runners and is unknown in female runners. Thus the purpose of this study was to examine the change in female running mechanics throughout a simulated 10 km running race in a controlled environment. We hypothesized that running mechanics would change as fatigue accumulated.

MATERIALS AND METHODS

Participants

Nine female runners were recruited from the local running community via posters and word of mouth. Inclusion criteria were at least three years of running experience and participation in at least one competitive 10 km running race within the last six months, with a 10 km race time between 35 and 48 minutes. Characteristics of included participants are provided in Table 1. The study was approved by the Local

Research Ethics Board (Pro00015884). Written informed consent was obtained prior to any research procedures being completed.

Table 1. Subject characteristics.

ID	Age (yrs)	Height (cm)	Mass (kg)	VO_2max (L/min)	VO_2max (ml/kg·min)	10 km Time Trial (min:ss)	10 km Time Trial - Slowest Lap (min:ss)	10 km Time Trial - Fastest Lap (min:ss)
A1	33	162.5	54.6	3.3	59.8	38:28	01:34	01:29
B2	31	159.5	50.3	3.0	58.8	41:43	01:45	01:33
C3	25	181.0	69.2	3.7	53.0	42:34	01:52	01:30
D4	34	170.0	59.0	3.7	62.9	39:50	01:39	01:32
E5	30	174.0	62.6	3.7	58.5	45:30	01:52	01:45
G7	30	161.5	62.5	3.1	49.4	46:49	01:58	01:43
H8	39	161.0	48.2	2.4	49.7	46:46	02:03	01:48
I9	37	161.0	51.6	2.7	51.5	47:32	02:02	01:43
J10	30	170.0	62.0	3.7	60.3	38:17	01:35	01:27
AVERAGE	32.1	166.7	57.8	3.2	56.0	43:03	01:49	01:37
SD	4.2	7.4	7.0	0.5	5.1	03:43	00:11	00:08

Measures

Marker data were used for rigid-body modelling in Visual 3D software (version 4.82; C-Motion, Germantown, MD, USA). Lower extremity markers were used to model the pelvis, and left and right thigh, shank and foot segments. Step frequency was defined as the measured rate over time from heel strike to heel strike of the same limb. Step length was defined by the measured distance from heel strike to heel strike of the same foot and was calculated by dividing the treadmill speed by the stride frequency. Maximum knee flexion (MKF) and extension (MKE) was defined as the maximum relative joint angle measured between the thigh and shank with MKE occurring prior to heel contact and MKF measured during the mid-swing phase. Maximum hip flexion (MHF) is the maximum positive absolute joint angle with respect to vertical. Hip Height (HH) was measured as the distance from the floor to the center of gravity of the pelvis.

Fatigue was evaluated two different ways: rating of perceived exertion assessed after mechanical data was taken during the treadmill trial; and measuring maximal voluntary contraction – MVC of knee extensors on a pulley-type leg extension machine instrumented with a force transducer in-line with the pulley cable before and after the treadmill trial. Data was sampled at 100 Hz using the APAS system by Ariel Dynamics through a Compute board 12 bit A/D board model.

Procedures

Testing occurred over three separate days with at least 48 hours between tests. The first test day consisted of neuromuscular and musculoskeletal exams to ensure participants were free from injury and/or bilateral differences in movement patterns. Participants then performed a graded exercise test on a treadmill to determine maximal oxygen uptake. Data was collected using a Parvo Medics' TrueOne® 2400 metabolic cart (Salt Lake City, Utah, USA).

Following at least 48 hours of rest, participants completed a 10 km time trial on a level 400-meter track. Participants were instructed to run as fast as possible for the duration of the 10 km run. Lap times were recorded with a stopwatch and recorded on a lap count recording sheet.

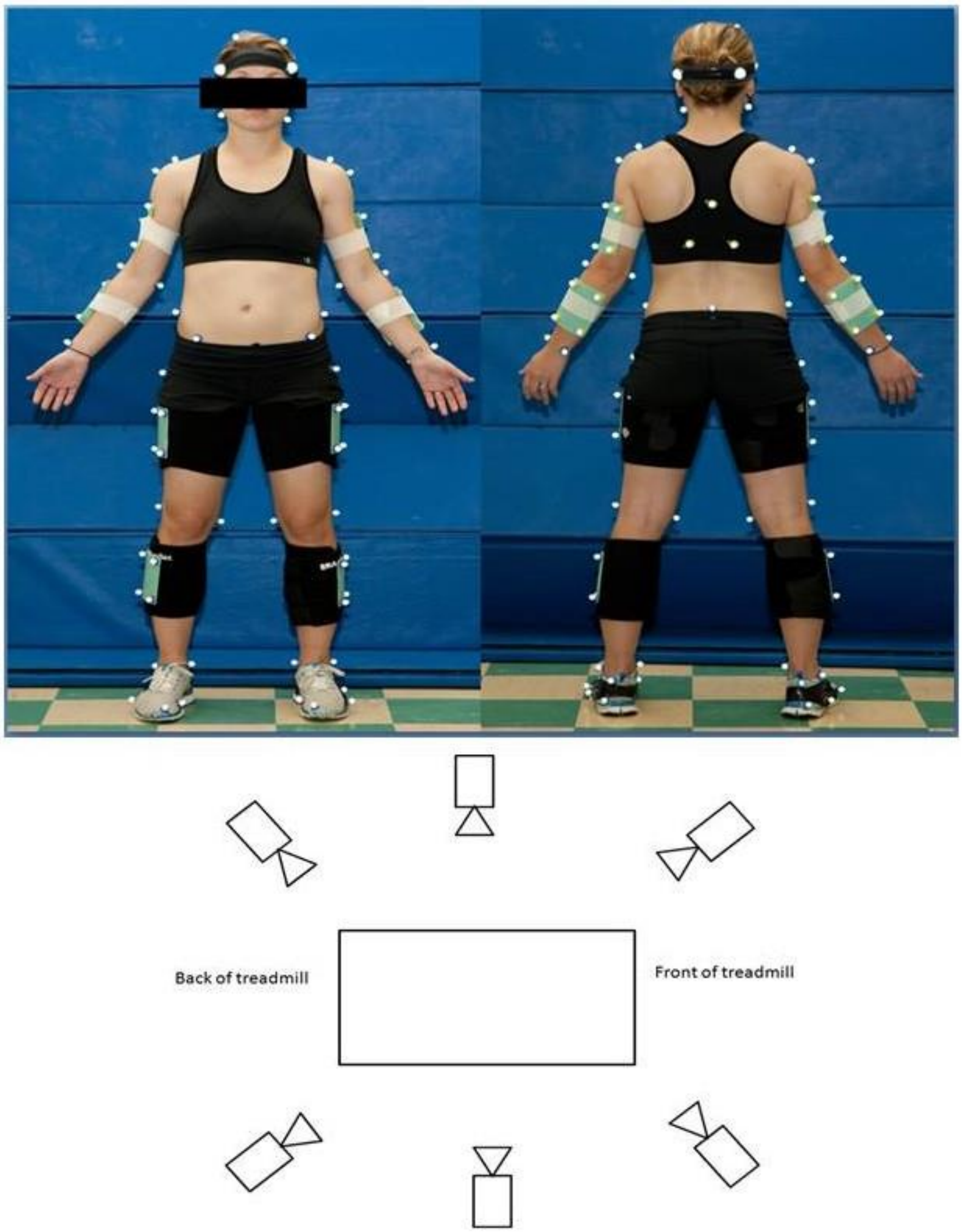

Figure 1. Diagram of marker and camera placement.

During the third testing day, participants were fitted with 82 retro-reflective markers using a six-degree of freedom (6-DOF) configuration of calibration and tracking markers. Calibration markers were placed on the proximal and distal ends of anatomical segments based on palpation of bony landmarks (Figure 1). Locations where skin was exposed were cleaned using alcohol swabs and coated with adhesive spray to ensure that markers did not fall off during running. The treadmill used for the simulated 10 km run was an 8700 Sprint Landice treadmill (Randolph, New Jersey, USA). Treadmill velocity was calibrated prior to each participant's simulated run. Treadmill velocity corresponded to 95% of subject's 10 km time trial velocity. Marker coordinate data were recorded for 50 m during specific intervals throughout the 10 km's using six ProReflex MCU240 cameras at 120 Hz with Qualisys Track Manager (version 2.3.410; Qualisys, Gothenburg, Sweden). Participants warmed-up at 60% of their calculated treadmill running speed for 1 minute. Treadmill velocity was increased 5% every 1 minute until 90% of speed was reached. Participants then stretched and rested for 5 minutes. Treadmill velocity was set to 95% of 10 km time trial velocity and participants were instructed to run to volitional exhaustion. Mechanical results were obtained at 50 m, 1450m, 2950m, 4450m, 5950m, 7450m, 8950m and 9950m. Each participant's mechanical results were measured for at least 5 consecutive strides and averaged for each distance. The first interval, 50-100m, was used as a baseline measure which represented the participant's usual non-fatigued running pattern. Participants were provided with a fan during the simulated 10 km trial and was turned on or off at the request of the participant.

Data Analysis

To determine the effect of fatigue over the trial each dependent variable was analyzed with a 1 x 8 repeated measures ANOVA. Significance was set a priori at $P < 0.05$. All statistical analysis was performed using SPSS for Windows 23.0. Sources of significant differences were determined using a Tukey post-hoc test. Reported means and standard deviations were determined using SPSS.

RESULTS

Isometric force measured during knee extension MVC was not significantly reduced following the simulated 10 km trial (MVC Pre: 503N ± 111 vs. MVC Post: 476N ± 156; p=0.17). Seven of the nine runners had a decrease in force production ranging from 1% to 21%. There was a main effect for rating of perceived exertion throughout the simulated 10 km run with a significant increase across all time points (Table 2). Perceived exertion ranged from light (12±1) at the beginning of the simulated run and progressed to maximum effort (19±1 on a 20 point scale) prior to completion.

Table 2. Rating of perceived exertion (RPE) throughout the simulated 10-km run. There was a main effect for RPE.

Distance (m)	Rating of Perceived Exertion
50	12 ± 1
1450	13 ± 1
2950	14 ± 1
4450	15 ± 1
5950	16 ± 1
7450	17 ± 1
8950	18 ± 1
9950	19 ± 1

Mechanical variables are reported for each measurement time point during the simulated 10 km run in Table 3. Step Frequency decreased significantly from 93.2 ± 5.3 steps/min at baseline to 90.2 ± 4.3 steps/min at 9950 m. While all distances showed a decrease in step frequency from baseline, this decrease was not statistically significant (Table 3). The decrease in step frequency was not incremental with a decrease to 4450 m then an increase at 5950 m and then a subsequent decrease to the lowest step frequency at 9950 m (Table 3). Step length, measured from heel strike to heel strike of the same limb, increased significantly from baseline to 9950 m (50m: 1.18m ± 0.10; 9950 m: 1.21m ± 0.10; p=0.04). The largest increase in step length occurred at 9950 m with little difference from baseline at all other time points.

MKE did not change significantly however an increase in step frequency at 5950 m coincided with a delta change of 0.74° from 4450 m to 5950 m. MHF was significantly increased from 2950m until the end of the simulated race with a mean total increase of 4.40°. MKF was significantly increased 4.27° from start to end of the run (Table 3) with a significant increase from 8950 m to 9950 m of 2.55° as well (Table 3). Hip height (HH) as measured as the distance from the floor to the centre of gravity of the pelvis. The group mean was 1.04±0.09 m at 50m. HH remained constant until 4450m where it dropped to 1.03±0.09 m (p>0.05).

Table 3. Means (± SD) of mechanical data across all distances of the simulated 10 km run. * significant difference from the previous measurement; † significant difference from 50m.

Distance (m)	Step Length (m)	Step Frequency (step/min)	Max Knee Extension (º)	Max Hip Flexion (º)	Max Knee Flexion (º)	Hip Height (m)
50	1.18 ± 0.10	93.2 ± 5.3	0.1 ± 7.0	53.3 ± 12.3	-97.4 ± 6.6	1.04 ± 0.09
1450	1.18 ± 0.10	92.7 ± 5.2	0.3 ± 7.5	53.7 ± 11.8	-97.9 ± 8.3	1.04 ± 0.09
2950	1.19 ± 0.10	92.0 ± 4.6	-0.4 ± 7.2	55.1 ± 12.4†	-98.3 ± 8.8	1.04 ± 0.09
4450	1.19 ± 0.10	91.9 ± 4.8	0.2 ± 7.7	55.3 ± 12.3†	-98.3 ± 8.2	1.03 ± 0.09
5950	1.18 ± 0.09	92.7 ± 4.8	-0.5 ± 7..5	54.7 ± 11.5	-96.7 ± 6.7	1.03 ± 0.09
7450	1.18 ± 0.09	91.9 ± 4.1	-0.5 ± 8.2	55.6 ± 12.6	-98.8 ± 8.1	1.03 ± 0.09
8950	1.19 ± 0.09	91.6 ± 4.6	-0.4 ± 7.5	55.1 ± 13.4†	-99.1 ± 8.6	1.03 ± 0.09
9950	1.21 ± 0.10*	90.2 ± 4.3*	-0.9 ± 7.3	57.7 ± 12.9*†	-101.7 ± 9.3*†	1.03 ± 0.09

DISCUSSION

Results from the present study indicate that changes in running mechanics are likely the result of accumulated fatigue as indicated by RPE which has been shown to be a gold standard measure of global physical strain in whole body exercise such as running (Borg, 1982). In this study, the increase in RPE from 12.2 (fairly light) to 19.4 (very, very hard) indicates that feedback from working muscles and the cardiovascular, respiratory and central nervous systems all likely contributed to this increase in RPE (Borg, 1982). Our results confirm that whole body fatigue in motivated runner's influences exertion as measured by RPE and that this increase in exertion is associated with compensatory changes in running mechanics.

Stride frequency continually decreased throughout the simulated 10 km run. This decrease in stride frequency was similar to those reported by Mizrahi (Mizrahi et al., 2000), where they found a reduction of 0.07 Hz or 3.20 strides/min and Candau (Candau et al., 1998), 0.05 Hz or 3.00 strides/min during treadmill runs to volitional exhaustion with male runners. This may indicate that the magnitude of change in stride frequency between male and female runners is similar. However, during a similar distance of 10 km, Hanley and Mohan (Hanley & Mohan, 2014) showed only a small decrease in SF (0.03Hz from 1500m to 9500m). This might be related to the participants included in each study, specifically, Hanley and Mohan (Hanley & Mohan, 2014) recruited elite male runners (mean race time: 34:17 min:ss) compared to our athletes who were slower on average. However in our study the 2 of the 3 fastest participants (38:51 min:ss average for top 3 participants) actually increased their step frequency and one maintained their step frequency until 8950 m (at which point it dropped). Thus this data and that of Hanley and Mohan indicates that fitter runners do not have the same step frequency decrease that less fit runners do in simulated race pace runs. Further examination, in an even more homogenous group of female runners is needed as it is still unknown whether compensatory mechanisms are comparable across both male and female runners of similar caliber.

As participants progressed throughout the simulated run, small increases in step length were present. These increases did not prove to be statistically significant, but were similar in magnitude to previous work. The increase of 3 cm in the present study was comparable to increases shown by Siler and Martin (Siler & Martin, 1991) (an increase of 4.4 cm) and Hanley and Mohan (Hanley & Mohan, 2014) (an increase of 2cm) in elite male runners. This is also consistent with previous research where stride length increased between 2.0 and 8.0 cm (Cavanagh et al., 1985; Hanley & Mohan, 2006; Williams, Snow, & Agruss, 1991). Although not as large as other studies have shown, our results indicate that increases in step and stride length appear to be similar across genders. These findings further suggest that women and men rely on similar compensatory mechanisms to maintain running velocity, mainly runners increasing step length to compensate for the decrease in stride frequency throughout the fatiguing run (Hanley & Mohan, 2006; Siler & Martin, 1991). Moreover our results identify that the timing of step length increase is in the latter portions of the race (within 1 km of the end of the race or with approximately 10 % of the race remaining) timed with decreased step frequency.

Any differences in the magnitude of the decrease in step frequency and the increase in step length could be related to the method of fatiguing the runners and the time points where final mechanical data was measured. Compared to other research where the pace may have varied ± 30 % from their actual race pace (Siler & Martin, 1991) (Williams et al., 1991) (Cavanagh et al., 1985) our participants all ran the same relative intensity and that intensity was only 5 % less than their free running time trial. In addition previous research only evaluated the running mechanics at termination, thus accurately represents mechanical changes that occur throughout a 10 km run. As stated previously, our velocity also represented a current 10 km race pace for each participant and this resulted in only 1 of the 9 participants able to continue past the 10 km mark. And this participant was still only able to run an additional 500 m. Thus our data provides well controlled evaluation of performance throughout a race compared to other research investigating running mechanics during simulated running races.

Previous research examining changes in stride frequency and mechanical changes in running at a constant pace has been decidedly mixed. One study has shown a decrease in stride frequency at a constant treadmill velocity occurs in conjunction with an increase in the vertical displacement of the pelvis (Anderson, 1996) and others whereby there was no significant increase in the average hip heights at maximal flight (Mizrahi et al., 2000). Results from our study suggest that the center of mass of the pelvis decreased but the magnitude of the change is small (8 participants decreased 1cm and 1 participants did not change) where the timing of the decrease was between 4450 – 5950 m in those participants whom decreased. In our study step frequency did not decrease until the last 1km thus any decreases in centre of mass likely did not influence step frequency. However our results do provide some insight into step length. By examining the increase in maximum hip flexion and decrease in maximum knee extension in combination, it may be hypothesized why step length remained relatively constant and then was lengthened. If there was only an increase in maximum hip flexion and maximum knee extension stayed constant, step length would increase because of a larger displacement of the hip. The opposite is also true, if maximum knee extension decreased, knee angle prior to heel contact would be larger and there would be a decrease in step length with a constant maximum hip flexion. Thus, the combination of decreased maximum knee extension and increased maximum hip flexion likely maintained step length in our study until the last kilometre where a significant increase in hip flexion caused a significant increase in step length (Table 2).

Maximum knee flexion during swing also increased throughout the simulated run and indicates that runners tried to decrease the moment of inertia of the leg about the hip joint to assist in reducing the inertial resistance of the limb. This has been shown to assist in bringing the leg through the swing phase to the next heel contact in non-fatigued running (Williams et al., 1991). This would have the potential effect of reducing the torque acting on the hip flexors and the metabolic demands of the hip flexor muscles as they fatigue (Williams et al., 1991). However it is likely that this mechanical change might also increase activation of the hamstrings and gastrocnemius-soleus complex's and associated increased metabolic demand of these muscles. To better understand how mechanical changes influence metabolic demands of muscle groups further studies examining tissue oxygenation in the major muscle groups of the leg as runners fatigue is warranted.

Given the fact that the simulated 10 km race was at a constant velocity it may be hypothesized that those with a more consistent pace profile from the free running trial may have less fatigue in the latter portions of the treadmill trial. We found that the participants with the 3 fastest 10 km times maintained a more consistent 400 m lap time (5, 7 and 8 seconds maximum deviation) compared to the compared to slower participants whose lap times varied by as much as 22 seconds (Table 1). This supports previous research (Lima-Silva et al., 2010) which also found that better (faster) runners intuitively use a more constant pace strategy for a free running trial with more even energy distribution over the duration of the trial. This approach to energy distribution has also been shown to reduce accumulated fatigue (Abbiss & Laursen, 2008) thus our better runners theoretically may have coped with fatigue differently than our slower runners. However the participants with a constant pace model in the simulated race also maintained step frequency (as discussed previously) but had mechanical changes which were similar to those slower participants who had wider variation in their free running pace profile. Thus, it is clear that compensatory changes in running mechanic occur in female runners of all abilities however faster runners seem to employ more constant pace strategies and this may improve how they cope with accumulated fatigue throughout a race.

CONCLUSIONS

The present research provides insight into how accumulated fatigue is managed by female runners throughout a simulated 10 km run. The mechanical analysis provides good evidence for compensatory mechanisms used at different portions of a running race and how training programs might be influenced to reduce some of the more significant changes. Although a cause and effect relationship between fatigue and mechanical changes is not definitive this data provides hypotheses that would support why mechanics might change in the latter portion of the race.

Coaches and sport scientists could apply these results by designing workouts which encourage step frequency maintenance in fatigued states. Further research on how verbal/visual feedback to maintain step frequency influences running fatigue, mechanics and performance is warranted. Specifically additional research might illuminate whether the change in step frequency is a result of mechanical coping strategies at their limit or is an intrinsic aspect of the relationship between mechanical running changes to maintain velocity.

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