CHANGES IN GAIT DURING CONSTANT PACE TREADMILL RUNNING

Running head: Gait changes during treadmill running

Biomechanics laboratory, Carnegie Research Institute

Brian Hanley and Anna Mohan

School of Sport, Carnegie Faculty, Leeds Metropolitan University, Leeds, UK

Brian Hanley,

Headingley Campus,

Carnegie Faculty of Sport and Education,

Leeds Metropolitan University,

Leeds, LS6 3QS,

United Kingdom.

Telephone: +44 113 812 3577

Fax: +44 113 283 3170

Email: B.Hanley@leedsmet.ac.uk

There was no external funding for this work.

ABSTRACT

Treadmills are often used by runners when weather conditions are adverse or a specific training effect is desired. Athletes might respond to fatigue differently when running on a treadmill compared with overground conditions, where pace is typically more variable. The purpose of this study was to measure changes in gait parameters over the course of a 10 km treadmill run. Fifteen male competitive runners ran at a constant pace for 10 km at 103% of season’s best time on an instrumented treadmill with in-dwelling force plates, and data were analyzed at five distances. Kinematic data were derived from high-speed videography and results compared between the early and late stages. Prior to halfway, step length increased and cadence decreased, while during the latter stages there were significant decreases in impulse and maximum force. Contact time decreased and flight time increased continually, but otherwise most gait variables did not change. The changes in contact and flight times suggested athletes altered their gait so that more time was spent airborne to allow the treadmill to pass under them. In general, however, the runners maintained their techniques throughout the run. Constant pace treadmill running might therefore be useful with the aim of running for a particular distance and speed with a consistent technique unaffected by factors such as gradient or fatigue. However, the increase in flight time might have aided the runners due to the nature of treadmill running, and athletes and coaches should note that this training effect is impractical during overground running.

Key words: athletics; biomechanics; coaching; endurance; fatigue; kinetics.

INTRODUCTION

Distance running is a popular activity for both recreational and competitive athletes, and at the Olympic Games competitions are held over 5000 m, 10000 m and the marathon. While the 5000 m and 10000 m are held on the track and the marathon on the road, other surfaces are popular with runners, such as trails and sand. Coaches often develop training regimens with different surfaces in mind, for example grassy hills for strength development (20). Treadmills are a form of equipment often used by both recreational and competitive runners. From a training viewpoint, using a treadmill indoors provides many advantages: avoidance of adverse weather conditions, such as ice or rain; the maintenance of an even, unchanging surface; and the ability to set a specific running speed for a desired duration (20). Such benefits mean that the athlete can achieve high-quality workouts that might otherwise have proven impossible.

While it is possible to use treadmills for training sessions such as short repetitions, they are also suitable for running relatively long distances. During treadmill running, the pace can be maintained at a constant speed for substantial portions or for the whole training session. By contrast, variations in pace are normal for distance runners in competition (19,30,31) and kinematic gait changes are typically exhibited with the onset of fatigue, the most noticeable being a reduction in running velocity due to both decreased cadence (9,14) and decreased step length (6,9,14). Previous research on the fatiguing effects of treadmill running has conversely found increases in step length (28,33); however, the protocols adopted in these studies required the subjects to run to exhaustion (i.e. until they felt they could no longer continue at the set pace) and such pacing profiles are rarely used by distance runners (13,19,30) where fatigue normally leads to slowing down (8) so that the training session or race can be completed (30). In exploring the biomechanical value of treadmill training to distance runners, it would therefore be interesting to investigate the effects of fatigue during constant pace treadmill running.

Aside from any training gains, a key benefit of using treadmills is the ease of technical monitoring for the coach, particularly if biomechanical or physiological testing occurs in tandem. Advantages of treadmills for laboratory testing include control of the settings and environment, thus reducing extraneous and confounding variables (22), while treadmills incorporating force plates additionally eliminate the effects of targeting which is often prevalent within gait analysis. Previous research has suggested that while there might be small kinetic and kinematic differences between overground and treadmill walking (2,26), the two are essentially equivalent (25,26). It has also been found that such differences disappeared after a familiarization period of 6 minutes (21). Furthermore, using a constant belt speed reduces the differences between overground and treadmill running and is therefore recommended (27,32) not only for testing, but also for those athletes wishing to carry out treadmill training that will transfer to overground running.

In competitive situations, distance athletes often vary pace due to tactics and it is not unusual to observe greater running speeds at the beginning and end of the race (19,30,31). Athletes suffering from pain or high levels of fatigue frequently reduce pace, but athletes who decide to complete a physically demanding treadmill run with a constant speed do not have this option. Instead, kinetic and kinematic changes might occur that allow the runner to maintain pace. Notwithstanding that treadmills can be used for different paced training and that athletes train at various paces (10,11), it would be beneficial for competitive distance runners and their coaches to know what changes occur when using a treadmill for constant pace training in order to assess the benefits and limitations of this particular form of training.

Furthermore, it would be useful for researchers who use treadmills (whether instrumented or not) to know if gait changes occur that might have an effect on their results or interpretation. The aim of this study was to measure gait variables during the course of a 10 km treadmill run. It was hypothesized that running kinetics, kinematic, and temporal variables would change due to fatigue induced by a physically demanding run.

METHODS

Experimental Approach to the Problem

A within-subjects repeated measures design was used to assess changes in running gait parameters (kinetics, kinematic and temporal) during a fast 10 km treadmill run. Subjects attended the laboratory on a single occasion and ran at close to their most recent best performance. Gait variables were measured using in-dwelling force plates and video analysis. The treadmill belt was kept at a constant speed in order to measure changes in these variables due to distance run rather than due to changes in pace.

Subjects

Fifteen male competitive distance runners (age: 32.4 ± 7.0 years, height: 1.78 ± .07 m, mass: 65.1 ± 6.7 kg) participated in the study. All participants were healthy and free from injury and had competed in a 10 km race within the previous four weeks; this race was held in cool temperatures (late November) on a flat, fast road course. The participants' finishing times for the 10 km race ranged from 30 to 35 minutes and the athletes specialized over distances from 5 km to half-marathon. The faculty ethics committee approved the details of the study including consent documentation and information to participants prior to commencement. In accordance with the Institutional Review Board's policies for use of human subjects in research, all subjects were informed of the benefits and possible risks association with participation, and were informed of their right to withdraw at any point. All participants were over the age of 18 and gave written informed consent to indicate their voluntary participation.

Procedures

Following a 10-minute warm-up and familiarization period, each subject ran for 10 km on a treadmill (Gaitway, Traunstein) at a pace that resulted in a running time equivalent to 103% of their recent race times (which in all cases was their season's best). The average treadmill speed during testing was 17.49 $km \cdot h^{-1}$ (± 0.62) and each athlete ran at a constant pace for the duration of the test. The treadmill's inclination was set at 0% during data collection (1). Although a 1% treadmill inclination is recommended for extrapolation of data generated by physiological assessment to outdoor road running (16), it was decided to use no inclination in this study to avoid any possible effects of gradient on running kinetics or kinematics. The treadmill incorporated two in-dwelling piezoelectric force plates (Kistler, Winterthur) that recorded vertical ground reaction forces (1000 Hz) from both feet as well as contact time. The force plates also recorded the position of the center of pressure (COP) from which stride length and stride width were measured. Data were collected for 30 seconds on 5 occasions during the run, beginning at a calculated time that resulted in the midpoint of data collection coinciding with 1500 m, 3000 m, 5000 m, 7500 m, and 9500 m of total distance run. The subjects wore their own competitive clothing during testing (i.e. running vest, shorts, and racing shoes). The Rate of Perceived Exertion Scale (RPE) (5) was used to measure levels of fatigue. The treadmill control panel was concealed during testing to prevent the athletes from monitoring their progress too often; however, they were informed when they reached each successive kilometer (similar to road race conditions). A fan was placed in front of the subjects to help cool them, and bottled water was available upon request.

Two-dimensional video data were simultaneously collected at 250 Hz using a high-speed camera (RedLake, San Diego). The shutter speed was 1/500 s, the *f*-stop was 2.0, and there was no gain. The camera was placed 5.3 m from and perpendicular to the treadmill. The resolution of the camera was 1280 x 1024 pixels. Extra illumination was provided by two 1250 W lights placed at the side of the camera. Prior to each testing session, two 3 m high reference poles were placed in the center of the camera's field of view in the center of the treadmill and used later for calibration. Because of time constraints, only the first and last recordings of each run (1500 m and 9500 m) were analyzed. The video files were manually digitized by a single experienced operator to obtain kinematic data using motion analysis software (SIMI Motion, Munich). Each video was first digitized frame by frame and adjustments were made as necessary using the points over frame method (3). The magnification tool in SIMI Motion was set at 400% to aid identification of body landmarks. Digitizing was started at least 10 frames before the beginning of the stride and completed at least 10 frames after to provide padding during filtering (29). Dropout occurred on the left hand side of the body on some occasions and estimations were made by the operator. The kinematic data were filtered using a recursive second-order low-pass Butterworth digital filter (zero phase-lag) of 10 Hz. De Leva's (7) body segment parameter model for men was used to obtain center of mass data for the whole body (CM) and both feet. Joint angular data were also derived from the digitized body landmarks.

Step length was defined as the distance from one foot strike to the next foot strike of the opposite foot. Contact time was defined as the time duration from initial contact to toe-off, while flight time was the time duration from toe-off of one foot contact to the initial contact of the opposite foot. Stride width (also known as base of support) (18) was defined as the average distance between a foot's mediolateral COP and the next opposing foot's COP for each foot strike. Impulse was defined as the integral of the vertical force-time curve for each foot strike.

Impact peak was defined as the highest recorded force during the first 70 ms of contact with the treadmill, while the maximum force occurred in all cases during the propulsive peak. Weight acceptance was the slope of the force curve during the early loading phase, taken from the point of 10% of the impact peak force to the point of 90%, while the push-off rate was the slope of the force curve during late stance unloading, taken from the point of 90% of push-off peak force to the point of 10%. To account for differences in body size, all force data were normalized by dividing the values (in newtons) by the athletes' weights and expressing as bodyweights (BW). All kinetic, kinematic and temporal variables were measured for both left and right legs and averaged for the purposes of this study.

With regard to angular kinematics, the hip angle was defined as the sagittal plane angle between the trunk and thigh segments and was considered to be 180° in the anatomical standing position. The knee angle was calculated as the sagittal plane angle between the thigh and leg segments and was also considered to be 180° in the anatomical standing position. The ankle angle was calculated in a clockwise direction using the leg and foot segments so that the angle of the ankle was approximately 110° in the anatomical standing position (14). Joint angular data have been presented in this study at initial contact and toe-off. Initial contact was defined as the first visible point during stance where the athlete's foot clearly contacts the ground, while toe-off was the last visible point during stance before the foot clearly left the ground. 'Foot ahead' was the term used to describe the distance from the center of mass of the landing foot to the body's overall CM. Similarly, 'foot behind' was the distance from the center of mass of the toe-off foot to the body's overall CM.

Statistical Analyses

In order to measure any changes in the variables obtained using the treadmill force plates, one-way repeated measures ANOVA was conducted with repeated contrast tests conducted to establish significant differences between successive measurement points (12,17). An alpha level of 5% was set for these tests with Greenhouse-Geisser correction used if Mauchly's test for sphericity was violated. The effect size was reported using partial eta-squared (η_p^2). The kinematic data that were obtained using the high-speed video recordings were compared using dependent *t*-tests; 90% confidence intervals (90% CI) were also calculated (4) and mechanistic magnitude-based inferences calculated using a dedicated spreadsheet designed by Hopkins (15) with a smallest worthwhile effect of 0.5%.

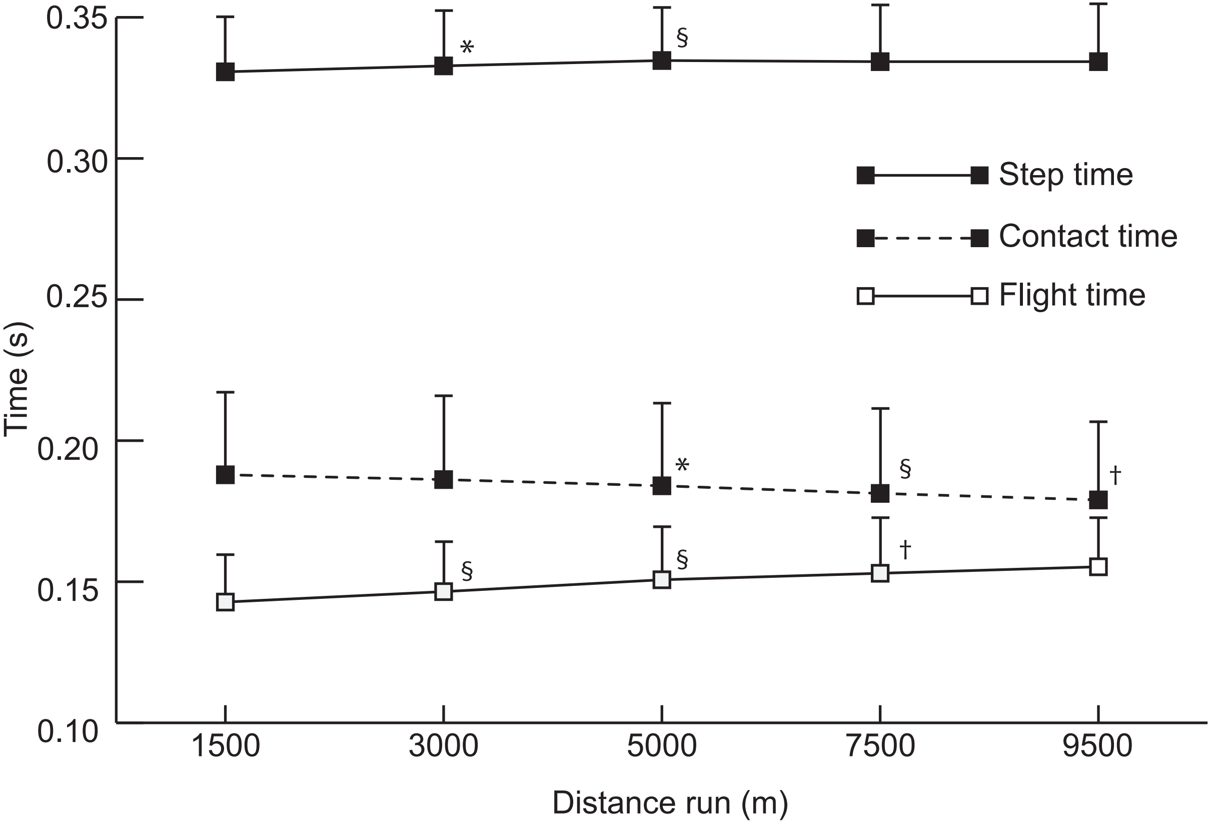
RESULTS

The mean RPE score at 1500 m was 11 (± 1), while it was 12 (± 1), 15 (± 2), 16 (± 2) and 18 (± 3) at the four subsequent measurement distances. In terms of foot-strike patterns, 11 of the athletes were heel-strikers while the other 4 were midfoot-strikers; no individual altered their foot-strike pattern with distance run. The values for the key performance variables of step length and cadence, as well as stride width and vertical impulse, are shown in Table 1. An increase in mean step length was found to occur ($F = 3.34$, $p = 0.016$, $\eta_p^2 = .193$, power = .813), with a corresponding decrease in cadence ($F = 3.88$, $p = 0.007$, $\eta_p^2 = .217$, power = .874). No differences were found for stride width; however, vertical impulse did decrease significantly ($F = 47.41$, $p < 0.001$, $\eta_p^2 = .772$, power = 1.000).

Table 1 Step length, cadence, stride width, and impulse (mean ± SD) at each distance

Distance	Step length (m)	Cadence (Hz)	Stride width (mm)	Impulse (N·s)
1500 m	1.61 ± 0.10	3.03 ± 0.18	50 ± 29	213 ± 31
3000 m	1.62 ± 0.11†	3.02 ± 0.18†	49 ± 30	212 ± 30
5000 m	1.63 ± 0.10†	3.00 ± 0.17*	48 ± 28	209 ± 29†
7500 m	1.63 ± 0.10	3.00 ± 0.19	48 ± 30	206 ± 29§
9500 m	1.63 ± 0.10	3.00 ± 0.19	51 ± 28	202 ± 29§

A significant difference from the previous measurement is denoted as $p < 0.001$ (§), $p < 0.01$ (*) or $p < 0.05$ (†) based on repeated measures contrasts.



0.35
0.30
0.25
0.20
0.15
0.10
Time (s)
1500
3000
5000
7500
9500
Distance run (m)
Step time
Contact time
Flight time
*
§
†

Figure 1 shows the mean step time at each measurement distance, as well as its two components, contact time and flight time. Significant decreases in contact time (F = 34.30, p < 0.001, η_p^2 = .710, power = 1.000) occurred in conjunction with significant increases in flight time (F = 37.51, p < 0.001, η_p^2 = .728, power = 1.000). As a result, the contact time proportion decreased from 56.6% of total step time at 1500 m to 53.4% at 9500 m (F = 51.59, p < 0.001, η_p^2 = .787, power = 1.000). Repeated measures showed that the contact time proportion decreased at every measurement distance compared with the previous distance (1500 m – 3000 m: p < 0.001; 3000 m – 5000 m: p = 0.001; 5000 m – 7500 m: p = 0.003; 7500 m – 9500 m: p = 0.021).

Table 2 Force data and loading rates (mean ± SD) at each distance

Distance	Maximum (BW)	Impact (BW)	Wt. acceptance ($BW \cdot s^{-1}$)	Push-off rate ($BW \cdot s^{-1}$)
1500 m	3.11 ± 0.21	2.33 ± 0.34	36.19 ± 9.67	31.50 ± 6.67
3000 m	3.12 ± 0.24	2.37 ± 0.34	36.33 ± 10.25	31.97 ± 6.70
5000 m	3.10 ± 0.24	2.39 ± 0.32	36.83 ± 10.62	31.92 ± 7.41
7500 m	3.06 ± 0.24*	2.37 ± 0.32	36.13 ± 10.04	31.98 ± 7.01
9500 m	3.05 ± 0.24	2.36 ± 0.30	35.65 ± 9.85	32.02 ± 6.79

A significant difference from the previous measurement is denoted as p < 0.01 (*) based on repeated measures contrasts.

Table 3 Means (± SD) of kinematic variables during the early and late stages of the treadmill running test.

	1500 m	9500 m	*p* value	90% CI
Initial contact				
Foot ahead (m)	0.33 ± 0.04	0.33 ± 0.04	.207	–.008 to .001*
Hip angle (°)	158 ± 6	157 ± 6	.623	–3.30 to 1.84†
Knee angle (°)	161 ± 6	159 ± 4	.006	0.93 to 3.20§
Ankle angle (°)	108 ± 7	108 ± 7	.589	–1.02 to 1.95†
Toe-off				
Foot behind (m)	0.46 ± 0.03	0.46 ± 0.04	.301	–.016 to .004*
Hip angle (°)	192 ± 2	193 ± 6	.281	–.80 to 3.60†
Knee angle (°)	162 ± 6	164 ± 5	.006	–3.92 to –1.15§
Ankle angle (°)	113 ± 8	113 ± 6	.456	–.60 to 1.54†

Magnitude-based inferences based on Hopkins (15) were found to be very likely positive (§), most likely trivial (*) or unclear (†).

Table 2 shows the results for the maximum force, impact peak force, weight acceptance rate and push-off rate. Maximum forces decreased as the run progressed, and this decrease was significant ($F = 7.45$, $p = 0.002$, $\eta_p^2 = .347$, power = 0.925). Table 3 shows the results for the kinematic variables measured at 1500 m and 9500 m; only the knee angle at initial contact and toe-off was found to differ.

DISCUSSION

The aim of this study was to measure how gait variables were altered during the course of a 10 km treadmill run. It was hypothesized that running kinetics, kinematics and temporal variables would change with distance run due to fatigue. While not all variables changed with distance run, some differences were found. Step length increased during the early stages of the run, and because the subjects ran at a constant speed, there was a corresponding decrease in cadence. However, the overall changes found (0.02 cm and 0.03 Hz respectively) were small (the effect sizes showed that distance run accounted for approximately 20% of variance) and the additional finding that no changes occurred after 5000 m suggests that there is little effect of fatigue on these two fundamental gait parameters. The small change in step length was most probably due to greater increases in flight time than due to foot positioning, as the effect sizes showed that any change in either the foot ahead or foot behind distances was trivial. There was no difference between the early and late-stage joint angles of the hip and ankle, and while the differences of 2° in the knee angle at both initial contact and toe-off were found using effect sizes to be very likely positive, they were within the boundaries of normal variation (26) and might not be a result of fatigue. In addition, there was no difference in stride width with distance run; the stability of this variable might be due to the need to maintain rearfoot motion to a subcritical value and thereby reduce the risk of injury (34).

The effect sizes found for the temporal variables showed that the majority of variance (> 70%) was accounted for by distance run and highlighted the most important changes found in the study. The small decreases in cadence that occurred up to halfway were a result of slightly longer step times. However, what was particularly striking was that at every measurement distance there was an increase in the proportion of time spent in flight compared with contact, in contrast with what occurs in fatigued distance runners in competition (14). While shorter contact times and longer flight times are generally associated with faster running (24), it is possible that during this fatiguing treadmill run the increase in flight time was a means of coping with the demands of the constant fast pace. Because treadmill running occurs by way of the athlete making repeated but brief contact with a moving belt (rather than pushing against a stationary surface), the runners in this study might have increased flight time so that more of the belt passed beneath them while they were airborne. The shorter contact times also resulted in a decrease in impulse with distance run and meant that the athletes applied less total vertical force during each step. Coaches and athletes should be aware that this response to fatigue is not normal or beneficial during overground running, and an overreliance on treadmill training could be counterproductive in this regard.

Overall, there were very few kinetic changes found during the fatiguing run. In early stance, impact forces and weight acceptance rates remained constant, and during late stance, a similar level of consistency was found in the push-off rates. From a training point of view, the treadmill is therefore a good method of ensuring consistent force application by the runner; this might be useful if the athlete wishes to undertake a session where the leg muscles (in particular) are stressed to the same level throughout. With regard to athlete testing, the few changes in kinetic and kinematic variables (and their small effect sizes) means that distance runners alter their gait very little during treadmill running and researchers can be confident that most changes observed (e.g. in running economy) are due to physiological factors. It is important to note though that a limitation of using the Gaitway treadmill is its inability to record shear forces and thus it is not possible to measure important gait variables that might have changed over the course of the run, or those that led to the important changes in contact time and flight time. For example, while increases in stride length and running velocity result from greater propulsive anteroposterior forces (23) it was unfortunately not possible to measure these or similar variables.

While it might be expected that most differences in gait parameters would occur during the later stages of running, this did not occur in practice. For example, the changes in step length and cadence occurred prior to halfway, whereas most of the changes in impulse and the decrease in maximum force occurred after 5000 m. It is possible that some early changes in gait might have been due to a warming-up effect, where the athletes took time to accustom themselves to the pace of the treadmill belt and the effort required. However, the decrease in contact time percentage at each successive measurement distance was indicative of a small but continuous alteration of running style that probably helped the athletes to complete the physically demanding distance run. In itself, the shortening of contact time and the increase in flight time is not negative and in fact could be a positive training outcome. Nonetheless, coaches and athletes should be aware that this aspect of treadmill training is only useful overground if an increase in horizontal rather than vertical movement is achieved. Understanding kinetic and kinematic changes during distance running is important for athletes and coaches. In addition to this study on constant pace treadmill running, it would therefore be useful for future research to measure changes in other training sessions typically used by distance runners such as interval training or long slow distance running, which is the most frequent form of endurance training (10,11).

PRACTICAL APPLICATIONS

The usage of a treadmill for a set distance and speed might be useful for those athletes who wish to become accustomed to running at a constant speed (with regard to physiological responses and pace judgment). The changes that occurred during a physically demanding 10 km treadmill run included increased step length, decreased cadence, and an increase in flight time. These changes would not necessarily be expected during an overground run (e.g. in competition) where the athlete would normally have a varied pace due not only to fatigue but also tactics and a faster endspurt. While gait variables changes were found using the treadmill, many were very subtle and further examination of the data using effect sizes showed that the practical importance of some changes was minor. For example, most differences in joint angles were trivial or unclear, while the effect of distance run on the two key kinematic variables of step length and cadence was only about 20%. Hence, this study has shown that there is little material change in kinetics or kinematics, and so athletes who use treadmills for training can be confident that technique is largely consistent (which might not be possible during overground running due to weather, changes in direction, or variations in terrain). Nonetheless, it should be noted that the effect sizes for changes in contact time and flight time were large (> 70%), suggesting that these changes were very much affected by distance run and could partly explain why the athletes were able to complete a fatiguing treadmill protocol without either needing to slow down or undergo major gait changes. Coaches should therefore take care when advising distance runners on the use of treadmills for hard training sessions as the increase in flight time thus showed that small and unconscious changes to running technique were made in order to ward off the effects of fatigue. As a result, treadmill usage should ideally be restricted to occasions when the surfaces used in competition (e.g. road, athletics tracks, grass) are inaccessible.

REFERENCES

1. Abt, JP, Sell, TC, Chu, Y, Lovalekar, M, Burdett, RG, and Lephart, SM. Running kinematics and shock absorption do not change after brief exhaustive running. J Strength Cond Res 25: 1479-1485, 2011.

2. Alton, F, Baldey, L, Caplan, S, and Morrissey, MC. A kinematic comparison of overground treadmill walking. Clin Biomech 13: 434-440, 1998.

3. Bahamonde, RE and Stevens, RR. Comparison of two methods of manual digitization on accuracy and time of completion. In: Proceedings of the XXIV International Symposium on Biomechanics in Sports. H. Schwameder, G. Strutzenberger, V. Fastenbauer, S. Lindinger, and E. Müller, eds. Salzburg, Austria, International Society of Biomechanics in Sports, 2006. pp. 650-653.

4. Batterham, AM and Hopkins, WG. Making meaningful inferences about magnitudes. Int J Sports Physiol Perf 1: 50-57, 2006.

5. Borg, G. Simple rating methods for estimation of perceived exertion. In: Physical Effort and Work. G. Borg, ed. New York: Pergamon Press, 1975. pp. 39-46.

6. Buckalew, DP, Barlow, DA, Fischer, JW, and Richards, JG. Biomechanical profile of elite women marathoners. Int J Sport Biomech 1: 330-347, 1985.

7. de Leva, P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J Biomech 29: 1223-1230, 1996.

8. Dutto, DJ and Smith, GA. Changes in spring-mass characteristics during treadmill running to exhaustion. Med Sci Sport Exerc 34: 1324-1331, 2002.

9. Elliot, B and Ackland, T. Biomechanical effects of fatigue on 10,000 meter running technique. Res Q Exerc Sport 52: 160-166, 1981.

10. Esteve-Lanao, J, Foster, C, Seiler, S, and Lucia, A. Impact of training intensity distribution on performance in endurance athletes. J Strength Cond Res 21: 943-949, 2007.

11. Esteve-Lanao, J, San Juan, AF, Earnest, CP, Foster, C, and Lucia, A. How do endurance runners actually train? Relationships with competition performance. Med Sci Sports Exerc 37: 496-504, 2005.

12. Field, AP. Discovering Statistics using SPSS (3rd edn.). London: Sage, 2009.

13. Haney, TA and Mercer, JA. A description of variability of pacing in marathon distance running. Int J Exerc Sci 4: 133-140, 2011.

14. Hanley, B, Smith, LC, and Bissas, A. Kinematic variations due to changes in pace during men's and women's 5 km road running. Int J Sports Sci Coaching 6: 243-252, 2011.

15. Hopkins, WG. A spreadsheet for deriving a confidence interval, mechanistic inference and clinical inference from a p value. Sportscience, 11: 16-20, 2007.

16. Jones, AM and Doust, JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. J Sports Sci 14: 321-327, 1996.

17. Kinnear, PR and Gray, CD. IBM SPSS Statistics 18 Made Simple. Hove: Psychology Press, 2010.

18. Levine, D, Richards, J, and Whittle, MW. Whittle's Gait Analysis (5th edn.). Edinburgh: Churchill Livingstone, 2012.

19. March, DS, Vanderburgh, PM, Titlebaum, PJ, and Hoops, ML. Age, sex, and finish time as determinants of pacing in the marathon. J Strength Cond Res 25: 386-391, 2011.

20. Martin, DE and Coe, PN. Better Training for Distance Runners (2nd edn.). Champaign, IL: Human Kinetics, 1997.

21. Matsas, A, Taylor, N, and McBurney, H. Knee joint kinematics from familiarised treadmill walking can be generalised to overground walking in young unimpaired subjects. Gait Posture 11: 46-53, 2000.

22. Nigg, BM, De Boer, RW, and Fisher, V. A kinematic comparison of overground and treadmill running. Med Sci Sports Exerc 27: 98-105, 1995.

23. Nummela, A, Keränen, T, and Mikkelsson, LO. Factors related to top running speed and economy. Int J Sports Med 28: 655-661, 2007.

24. Paavolainen, LM, Nummela, AT, and Rusko, HK. Neuromuscular characteristics and muscle power as determinants of 5-km running performance. Med Sci Sports Exerc 31: 124–130, 1999.

25. Riley, PO, Dicharry, J, Franz, J, della Croce, U, Wilder, RP, and Kerrigan, DC. A kinematics and kinetic comparison of overground and treadmill running. Med Sci Sports Exerc 40: 1093–1100, 2008.

26. Riley, PO, Paolini, G, della Croce, U, Paylo, KW, and Kerrigan, DC. A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. Gait Posture 26: 17-24, 2007.

27. Savelberg, HHCM, Vorstenbosch, MATM, Kamman, EH, van de Weijer, JGW, and Schambardt, HC. Intra-stride belt-speed variation affects treadmill locomotion. Gait Posture, 7: 26-34, 1998.

28. Siler, WL and Martin, PE. Changes in running pattern during a treadmill run to volitional exhaustion: fast versus slower runners. Int J Sport Biomech 7: 12-28, 1991.

29. Smith, G. Padding point extrapolation techniques for the Butterworth digital filter. J Biomech 22: 967-971, 1989.

30. Thiel, C, Foster, C, Banzer, W, and de Koning, J. Pacing in Olympic track races: competitive tactics versus best performance strategy. J Sports Sci 30: 1107-1115, 2012.

31. Tucker, R, Lambert, MI, and Noakes, TD. An analysis of pacing strategies during men's world-record performances in track athletics. Int J Sports Physiol Perf 1: 233-245, 2006.

32. van Ingen Schenau, GJ. Some fundamental aspects of the biomechanics of overground versus treadmill locomotion. Med Sci Sports Exerc 12: 257–261, 1980.

33. Williams, KR, Snow, R, and Agruss, C. Changes in distance running kinematics with fatigue. Int J Sport Biomech 7: 138-162, 1991.

34. Williams, KR and Ziff, JL. Changes in distance running mechanics due to systematic variations in running style. Int J Sport Biomech 7: 76-90, 1991.

Figure legends

Figure 1. Step time, contact time and flight time (mean + SD) at each measurement distance during the treadmill run. A significant difference from the previous measurement is denoted as $p < 0.001$ (§), $p < 0.01$ (*) or $p < 0.05$ (†) based on repeated measures contrasts.