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Kinematic Variations Due to Changes in Pace During Men's and Women's 5 km Road Running

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ABSTRACT The purpose of this study was to investigate variations in kinematic parameters in men's and women's 5 km road racing. Athletes often vary their pace and changes particularly tend to occur towards the end of a race due to fatigue and sprint finishes. Twenty competitive distance runners (10 male, 10 female) were videoed as they completed the English National 5 km championships. Three-dimensional kinematic data were analysed using motion analysis software (SIMI, Munich). Data were recorded at 950 m, 2,400 m and 3,850 m. Repeated measures ANOVA showed significant decreases in speed due to reduced step length and cadence in both men and women. These decreases predominantly occurred between the first two measurement points. The hip, knee, ankle and shoulder angles at both initial contact and toe-off did not change significantly, but there were significant reductions in the elbow angle for both men (at initial contact) and women (at toe-off).

Key words: Athletics, Gait, Kinematics, Pacing, Road Running

INTRODUCTION

Road running is an integral and growing area in athletics. The International Association of Athletics Federations (IAAF) designates Road Race Label Events at elite level [1] and competitions over several distances are held at international, national and regional level. Success in elite distance running is associated with high maximum oxygen uptake, high stroke volume, muscle fibre composition, and other physiological factors [2]. Psychological factors also play their part, especially pain tolerance [3]. With regard to running technique, biomechanical variables such as step length, cadence and lower limb joint angles are important in optimising speed and efficiency [4,5].

Running a distance race with an even pace throughout (or with a negative split, where the second half is faster than the first) is often considered the best strategy to achieve optimal performance [6]. However, competitors often have varied running speeds throughout a race with corresponding physiological and mechanical changes. In particular, running speed changes with fatigue, and this causes athletes to alter their techniques to try to maintain running economy [4]. Other variations in pace may occur due to tactical decisions. For example, some athletes choose to vary the pace considerably during a 5,000 or 10,000 metre race in order to challenge the physiological responses of the others [7]. In some instances, coaches might recommend their athletes to run faster than normal for the first mile of a race to establish a good position in the field [8]. Alternatively, runners may choose to position themselves behind other athletes to reduce energy cost, before increasing speed and overtaking towards the end of the race. This can be a sensible strategy as Kyle [9] estimated that there was a 40% reduction in air resistance (with a consequent 3% reduction in energy expenditure) when drafting two metres behind another runner.

From a biomechanical perspective, running speed is the product of step length and cadence [10]. Cadence is determined by the duration of step time, which itself is determined as the sum of contact time (i.e. time spent by the runner with the foot in contact with the ground) and flight time. At speeds lower than maximal (e.g., in long distance running), increases in speed are mainly reliant upon increases in step length, while increases in cadence become more important at faster speeds [11]. When running at their normal racing pace, well-trained athletes appear to unconsciously select the step length and cadence that minimise energy expenditure [12]. Buckalew et al. [10] found that decreases in running speed in female runners over the course of a marathon were caused primarily by a reduction in step length whereas cadence remained constant throughout. Over the course of a men's 10,000 metre track race, Elliot and Ackland [13] also found decreases in step length were significant (from 1.76 m in the first kilometre to 1.66 in the final kilometre). However, they too reported that cadence remained relatively constant [13].

Foot positioning at initial contact can affect running speed. Buckalew et al. [10] and Elliot and Ackland [13] reported that negative acceleration occurs due to a braking effect when the foot advances too far ahead of the body's centre of mass (CM) at initial contact. The position of the stance leg at initial contact depends on the joint angles of the hip, knee and ankle joints. For these variables, Elliot and Ackland [13] found very small changes in lower limb joint kinematics with fatigue in men's 10,000 m racing, but greater changes were found over the course of a women's marathon [10]. Williams et al. [14] suggested that with fatigue, runners should not markedly change their mechanics as this may exacerbate the effects of fatigue and increase the deterioration of technique, although fatigued athletes may find it very difficult to achieve this in practice.

Biomechanical research has in many cases used pre-determined constant running paces in order to measure effects of fatigue, either on a treadmill [8,15,16,17,18] or on a track [19]. A disadvantage of these approaches is that the responses to fatigue may not be consistent with situations where the pace is self-selected and exact speed is largely unknown. For example, Williams et al. [14] found that for the same athletes, step length increased with fatigue when using a treadmill protocol, but not in a competitive race. Running at a constant pace also does not necessarily reflect what occurs in a race where tactics, and the lead athletes in particular, can influence variations in pace [20]. With regard to race setting, differences may also occur in pacing accuracy between track racing (where every 100 metre section is marked) and road racing (where only each kilometre or mile is usually marked). It is therefore important to analyse changes in the kinematics of road running in a competitive setting where the athletes are running at variable paces, attempting to do their best, and the video analysis is external to the activity. This analysis will provide coaches and athletes with useful information about the effects of changes in pace on running mechanics and relevant training suggestions. Therefore the aim of this study was to measure changes in kinematic variables during 5 km road racing.

METHOD

PARTICIPANTS

The study was approved by the University's Research Ethics Committee. Video data were collected at the English National 5 km road race championships, held in Horwich, Great Britain. Ten male athletes and ten female athletes, competing in the same race, were analysed on three occasions. The analysis points were 950 m (referred to here as lap 1), 2,400 m (lap 2) and 3,850 km (lap 3). These athletes were chosen as they were the only competitors who could be seen clearly at all three recording points. The mean finishing time for the men was 14:59 (± 0:48) with a range from 13:56 to 16:21; the mean finishing time for the women was 16:43 (± 0:30) with a range from 15:45 to 17:28. Three of the men and three of the women had competed in the Olympic Games or World Championships (road or cross country).

DATA COLLECTION

Two stationary 3CCD DM-XL1 digital camcorders (Canon, Tokyo) were placed on one side of the course, approximately 45º and 135º respectively to the plane of motion. Each camera was approximately 9 m from the path of the runners. Based on the recommendations of the British Association of Sport and Exercise Sciences (BASES) [21], the sampling rate was 50 Hz and the shutter speed 1/500 s. The resolution of each camera was 720 x 576 pixels. This section of the course was chosen for camera placement due to the straightness of the course at that point and the absence of obstacles to the view of the cameras. The reference volume was 5.00 m long, 2.00 m wide and 2.16 m high. The calibration poles were placed so that the reference volume coincided with the path taken by most runners. These volumes were used later for calibration for 3D Direct Linear Transformation [22]. A calibration rod was digitised within the calibration volume and its calculated length compared to its known length. The root mean square (RMS) of the difference between the known and calculated values was 0.2% of the rod's length in the x-direction (length), 0.7% in the y-direction (height) and 0.8% in the z-direction (width).

DATA ANALYSIS

The video footage was manually digitised to obtain kinematic data using motion analysis software (SIMI, Munich). The video footage from each camera was synchronised manually by visual identification. Dropout occurred on the left hand side of the body on some occasions and estimations were made by the single experienced operator. Seventeen points were digitised for each participant. De Leva's [23] body segment parameter models for males and females were used to obtain data for the whole body CM and particular limb segments. Joint angular data were also derived from the digitised body landmarks. The recordings were smoothed using a cross-validated quintic spline [24,25]. The results for each side of the body were averaged for the purposes of this study.

Running speed was determined as the average horizontal speed during one complete gait cycle. Step length was measured as the distance the body travelled between a specific phase on one leg and the same phase on the other leg. Cadence was calculated by dividing horizontal speed by step length and the proportion of time spent by each leg in stance compared with swing was also measured as the stance time percentage. 'Foot ahead' was the term used to describe the distance from the centre of mass of the landing foot to the body's overall CM.

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 0° in the anatomical standing position, where negative values indicated hyperextension. The knee angle was calculated as the sagittal plane angle between the thigh and leg segments. 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. The shoulder angle value has been reported for the sagittal plane and was calculated using the coordinates of the hip, shoulder and elbow joint centres. The shoulder was considered to be 0° in the anatomical standing position, where negative values indicated hyperextension. The elbow angle was calculated using the shoulder, elbow and wrist joint centre coordinates.

Joint angular data have been presented in this study at two specific points of the gait cycle. These specific points are 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 where the foot clearly contacts the ground.

STATISTICAL ANALYSIS

Repeated measures ANOVA was conducted on the data recorded at three points with repeated contrast tests conducted to establish significant changes between successive measurement points. An alpha level of 5% was set for these tests with Greenhouse-Geisser correction used if Mauchly's test for sphericity was violated.

RESULTS

SPEED, STEP LENGTH AND CADENCE

The mean running speeds, step lengths and cadences for men for all three measurement points are shown in Table 1. The men's mean speed was significantly lower in lap 2 compared with lap 1 (p = .003), and was slightly lower in lap 3 compared with lap 2 (p = .323). This decrease in speed was accompanied by a decrease in cadence between laps 1 and 2 (p = .004), but there was no difference between laps 2 and 3 (p = 1.000). Mean step length decreased by 3 cm between laps 1 and 2 (p = .100) and by 2 cm between laps 2 and 3 (p = .125).

Table 1 Variation in speed, step length and cadence for men (mean ± SD)

Men	Speed (km/hr)	Step length (m)	Cadence (Hz)
Lap 1	21.43 (± 0.93)	1.86 (± .09)	3.20 (± .15)
Lap 2	20.50 (± 1.19)†	1.83 (± .13)	3.12 (± .16) †
Lap 3	20.29 (± 1.40)	1.81 (± .14)	3.12 (± .15)
Difference (%)	*-4.3, -1.0*	*-1.6, -1.1*	-2.5, 0.0

† Lap 2 significantly different from Lap 1 at the .005 level

The same variables are shown for women in Table 2. Their mean speed also decreased significantly between laps 1 and 2 (p < .001) but in contrast to the men, their mean speed was not lower at the lap 3 point compared with lap 2. The reduced speed at lap 2 compared with lap 1 was due to a cadence 0.06 Hz lower (p = .006) and a step length 0.07 m shorter (p = .008).

Table 2 Variation in speed, step length and cadence for women (mean ± SD)

Women	Speed (km/hr)	Step length (m)	Cadence (Hz)
Lap 1	19.46 (± 0.54)	1.68 (± .09)	3.23 (± .19)
Lap 2	18.32 (± 0.65) ‡	1.61 (± .08)*	3.17 (± .19) *
Lap 3	18.40 (± 0.57)	1.61 (± .08)	3.17 (± .20)
Difference (%)	*-5.9, +0.4*	*-4.2, 0.0*	*-1.9, 0.0*

‡Lap 2 significantly different from Lap 1 at the .001 level

*Lap 2 significantly different from Lap 1 at the .01 level

In Table 3, both groups of ten athletes have been listed in finishing order and allocated an identifying letter. The difference between successive laps has been described in terms of either an increase or decrease in pace as a percentage of the first measurement of the pair. Eight of the ten men and all ten women showed a reduction in pace between the first and second laps. The two men who increased speed between these points (Athletes A and C) were two of the three fastest athletes overall. The third athlete of the fastest runners (Athlete B) was one of only two men who increased their running speeds from lap 2 to lap 3. Athletes A, B and C were the three men who had competed in global championships. The fifth-fastest woman analysed, Athlete R, was the only athlete of the twenty to have a higher running speed on lap 3 compared with lap 1.

Table 3 Changes in pace for each individual athlete

Men	Lap 1 to 2 difference (%)	Lap 2 to 3 difference (%)	Women	Lap 1 to 2 difference (%)	Lap 2 to 3 difference (%)
A	+0.3	-1.5	L	-4.8	-1.3
B	-4.2	+2.9	M	-4.0	-0.3
C	+0.4	-2.6	N	-3.3	-3.2
D	-3.3	-0.2	P	-10.8	+2.2
E	-8.8	-1.4	R	-3.4	+4.3
F	-6.0	+5.2	S	-8.0	-1.8
G	-5.4	-3.1	T	-8.8	+1.5
H	-8.2	-6.5	U	-3.4	-0.8
J	-7.2	-1.4	W	-5.8	+2.6
K	-0.9	-2.0	X	-6.3	+1.5

STEP TIME, CONTACT TIME AND FLIGHT TIME

The sampling rate of the cameras was 50 Hz which meant that each individual's step time, contact time and flight time measurements were accurate to 0.02 s. The mean step time for both men and women on the first lap was 0.31 s (± .02) and was also the same for both groups on the second lap (0.32 ± .02) and the third lap (men: 0.32 ± .02; women: 0.32 ± .01). The mean values for contact time and flight time for men at each measurement point are shown in Table 4. There were no differences in contact time between successive laps, nor were there any differences in flight time. Stance time percentage is also shown in Table 4 and it also remained consistent at each measurement point at approximately 30%.

Table 4 Contact time, flight time and stance time percentage for men (mean ± SD)

Men	Contact time (s)	Flight time (s)	Stance time (%)
Lap 1	0.18 (± 0.01)	0.13 (± 0.02)	29 (± 2)
Lap 2	0.19 (± 0.01)	0.13 (± 0.02)	30 (± 2)
Lap 3	0.19 (± 0.01)	0.13 (± 0.01)	30 (± 2)

Table 5 shows the mean contact time, flight time and stance time percentage for the women athletes on each lap. Contact time did not increase from lap 1 to lap 2 (p = .096) nor from lap 2 to 3 (p = .343). Flight time also did not change significantly as the race progressed. As with the men's group, stance time percentage remained consistent at each point for the women, ranging from 31 to 33%.

Table 5 Contact time, flight time and stance time percentage for women (mean ± SD)

Women	Contact time (s)	Flight time (s)	Stance time (%)
Lap 1	0.19 (± 0.02)	0.12 (± 0.02)	31 (± 2)
Lap 2	0.20 (± 0.01)	0.11 (± 0.01)	32 (± 2)
Lap 3	0.21 (± 0.01)	0.11 (± 0.01)	33 (± 2)

RELATIVE POSITION OF THE FOOT AT INITIAL CONTACT

The distance between the body's centre of mass and the foot's centre of mass at initial contact ('foot ahead') was measured for each group. The mean foot ahead distances for men on laps 1, 2 and 3 were 0.33 m (± 0.05), 0.33 m (± 0.05) and 0.34 m (± 0.04) respectively. The women's group had similar values, with means of 0.33 m (± 0.05), 0.31 m (± 0.05) and 0.33 m (± 0.02) for each successive lap. The differences between laps were not found to be significant.

JOINT ANGLES AT INITIAL CONTACT

The mean absolute angle data at initial contact for men and women are shown in Tables 6 and 7 respectively. The hip joint angle represents the amount of hip flexion at this point, and both shoulder and elbow angles are taken from the ipsilateral arm to the contact leg. For most of the joints, the value of the angle remained consistent at each measurement point. Only the elbow showed any difference between laps: for men, the angle decreased by 5° between lap 1 and lap 2 ($p < .001$), and by 3° between laps 2 and 3 (p = .161). For women, the elbow angle decreased in a similar fashion, by 4° between laps 1 and 2 (p = .078) and then by 3° between laps 2 and 3 (p = .113).

Table 6 Joint angle measurements for men at initial contact (mean ± SD)

Men	Hip (°)	Knee (°)	Ankle (°)	Shoulder (°)	Elbow (°)
Lap 1	25 (± 5)	158 (± 4)	104 (± 4)	-46 (± 4)	70 (± 13)
Lap 2	26 (± 4)	157 (± 4)	104 (± 4)	-46 (± 4)	65 (± 13) ‡
Lap 3	25 (± 4)	158 (± 4)	106 (± 4)	-46 (± 4)	62 (± 12)

‡Lap 2 significantly different from Lap 1 at the .001 level

Table 7 Joint angle measurements for woman at initial contact (mean ± SD)

Women	Hip (°)	Knee (°)	Ankle (°)	Shoulder (°)	Elbow (°)
Lap 1	24 (± 5)	159 (± 4)	101 (± 4)	-51 (± 7)	72 (± 12)
Lap 2	24 (± 4)	159 (± 4)	101 (± 4)	-49 (± 7)	68 (± 13)
Lap 3	24 (± 5)	159 (± 4)	102 (± 4)	-52 (± 5)	65 (± 15)

JOINT ANGLES AT TOE-OFF

Tables 8 and 9 show the absolute angle data at toe-off for men and women respectively. As with the data at initial contact, there were few differences in joint angles between laps for either men or women. Only the elbow angle for women showed any significant difference, with a 6° decrease between laps 1 and 2 (p = .002), with no further change on lap 3 (p = .819).

Table 8 Joint angle measurements for men at toe-off (mean ± SD)

Men	Hip (°)	Knee (°)	Ankle (°)	Shoulder (°)	Elbow (°)
Lap 1	-20 (± 5)	164 (± 4)	128 (± 5)	26 (± 5)	60 (± 9)
Lap 2	-20 (± 4)	164 (± 4)	125 (± 5)	25 (± 4)	57 (± 9)
Lap 3	-21 (± 4)	165 (± 2)	124 (± 4)	24 (± 5)	55 (± 8)

Table 9 Joint angle measurements for women at toe-off (mean ± SD)

Women	Hip (°)	Knee (°)	Ankle (°)	Shoulder (°)	Elbow (°)
Lap 1	-19 (± 5)	163 (± 2)	126 (± 7)	31 (± 7)	64 (± 16)
Lap 2	-20 (± 4)	164 (± 2)	127 (± 7)	29 (± 7)	58 (± 17) †
Lap 3	-21 (± 4)	164 (± 3)	125 (± 4)	29 (± 7)	58 (± 12)

†Lap 2 significantly different from Lap 1 at the .005 level

DISCUSSION

Variations in pace were found for all twenty athletes analysed over the course of a 5 km road race. There was an overall reduction in pace for both men and women from the first measurement point to the last, and the majority of this decrease had occurred by the 2,400 m point. The three best athletes (A, B, and C) did not show the same pattern of slowing down as most of the others, and there may be a number of reasons for this. For example, they may train at faster paces and higher intensities more often and know what race pace should feel like; they may be better trained to withstand any effects of fatigue; or they may have used timing equipment to pace themselves (for example, as the race leaders they may have been able to see the lead car carrying the clock easier than those further back).

On average, men slowed down by 1.14 km/hr and women by 1.06 km/hr over the course of the race. The significant decrease in men's speed between laps 1 and 2 was primarily caused by a decrease in cadence of 0.08 Hz, although the reduction in mean step length of 3 cm was obviously an important factor also. This was seen again with the smaller decrease in speed between laps 2 and 3, where cadence did not change but step length decreased by 2 cm. Such small differences may not be statistically significant, but can be crucial in athletic competitions where winning margins can be extremely small (the final results showed that three seconds separated the first three men in this particular 5 km race). The women also had a large decrease in speed between laps 1 and 2, with significant decreases in both step length and cadence. Their average speed did not decrease again between laps 2 and 3 with both mean step length and cadence remaining constant. In longer races, previous research [10,13] has found decreases in step length but not cadence. The significant decrease in cadence for both men and women in this study between laps 1 and 2 may have been caused by a less conservative approach to pacing at the beginning, and a desire to establish a good position [8]. Starting too fast in a 5 km race is unlikely to lead to fatigue levels too great to complete the race, a more important consideration for the marathon runner. The small changes in the components of step time in both groups were too small to be meaningful with respect to the sampling rate of 50 Hz. Further research with higher sampling rates will allow for more accurate measurements of these variables.

The very small gain in mean speed for women between lap 2 and 3 was due to five women increasing their pace combined with relatively small decreases in speed for the others (ranging from –0.3 to –3.2%). It appeared from the video recordings that on laps 2 and 3 many of the analysed women had tucked in behind other women as well as behind male competitors. This may have had a slipstreaming effect with a consequential reduction in energy loss compared with lap 1 [9], as well as a pacemaking effect. While times set by women in mixed races on the track are not accepted by the IAAF (as either records or qualifying times) [26], such times are accepted if they were achieved in road races. It can be therefore advantageous to women to run in mixed road races where male runners can be used as pacemakers. For example, Paula Radcliffe had two male pacemakers for the entire duration of her world record marathon run in London in 2003.

The lack of changes in joint angles, position of the foot at landing, and step time characteristics is interesting. Neither men nor women showed any differences in lower leg kinematics despite overall decreases in step length and cadence, which was similar to findings in previous research [13]. Overall, athletes maintained their techniques (whether efficient or inefficient) at each pace. The only joint angle which showed any changes over the course of the race was the elbow. The reduction in the elbow angle as the race progressed brought the arm segments closer together and the resulting decrease in the moment of inertia may have made shoulder flexion and extension easier when fatigued. The elbow was also of interest as it had by far the greatest standard deviation of all angular measurements. Visually, there were large variations in the upper body positions adopted by athletes: some had very flexed elbows (the minimum angle was 42°) while others maintained much greater angles (a maximum of 102°). Athletes are recommended to develop efficient technique as well as the local muscular endurance of the upper body through appropriate strength and conditioning exercises. This assists in preventing changes in running mechanics that may exacerbate the effects of fatigue [14].

CONCLUSION

The aim of this study was to measure changes in kinematic variables during 5 km road racing. There are a number of important variables in running, the most important being step length and cadence as they determine speed. Both of these variables decreased as the race progressed, but athletes generally maintained the same joint angles and foot positioning at initial contact throughout the race. Athletes therefore appeared visually to have the same running technique at each measurement. Local muscular endurance is a key factor in maintaining step length and cadence. From the results, it appeared that most athletes in this race adopted a tactic of running as fast as possible for as long as possible, with subsequent reductions in pace due to fatigue. Only a small number of athletes ran either with a relatively constant pace or sped up towards the end of the race. Athletes are advised to run at different specific race paces in training so that they develop a sense of what each pace feels like. This can help the athlete to start a race at an appropriate pace for their ability rather than following that largely set by others. Women who had slowed considerably between laps 1 and 2 changed their tactics by following other athletes to pace themselves and reduce energy expenditure. It would seem prudent for athletes to incorporate this tactic earlier in the race to help prevent early fatigue.

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