GROUND REACTION FORCES OF OLYMPIC AND WORLD CHAMPIONSHIP RACE WALKERS

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Abstract

Race walking is an Olympic event where no visible loss of contact should occur and the knee must be straightened until midstance. The purpose of this study was to analyse ground reaction forces of world-class race walkers and associate them with key spatiotemporal variables. Nineteen athletes race walked along an indoor track and made contact with two force plates (1000 Hz) while being filmed using high-speed videography (100 Hz). Race walking speed was correlated with flight time (r = .46, p = .049) and flight distance (r = .69, p = .001). The knee's movement from hyperextension to flexion during late stance meant the vertical push-off force that followed midstance was smaller than the earlier loading peak (p < .001), resulting in a flattened profile. Athletes with narrower stride widths experienced reduced peak braking forces (r = .49, p = .046), peak propulsive forces (r = .54, p = .027), peak medial forces (r = .63, p = .007) and peak vertical push-off forces (r = .60, p = .011). Lower fluctuations in speed during stance were associated with higher stride frequencies (r = .69, p = .001), and highlighted the importance of avoiding too much braking in early stance. The flattened trajectory and consequential decrease in vertical propulsion might help the race walker avoid visible loss of contact (although nonvisible flight times were useful in increasing stride length), while a narrow stride width was important in reducing peak forces in all three directions and could improve movement efficiency.

Keywords: biomechanics, coaching, endurance, kinetics, performance

Introduction

Race walking is contested over 20 km (men and women) and 50 km (for men only) at the Olympic Games and all other major athletics championships. It is an abnormal gait dictated by a rule that states that no visible (to the human eye) loss of contact with the ground should occur and that the leg must be straightened from first contact with the ground until the 'vertical upright position' (Rule 230.1) (IAAF, 2013). The consequential absence of knee flexion during early- and midstance in race walking does not occur in normal walking (Lee & Farley, 1998) and prior research on race walkers has found that race walkers' knees are in fact usually hyperextended during midstance (Hanley, Bissas, & Drake, 2011; Hanley, Bissas, & Drake, 2013). It is possible that both this atypical movement of the knee and the need to avoid visible loss of contact have a considerable effect on ground reaction force (GRF) patterns that affect other gait variables.

As an endurance event, it is crucial that the athlete can maintain a fast but submaximal speed that wastes as little energy as possible. The main spatiotemporal factors that the athlete has to consider in achieving higher speeds are increased stride length and stride frequency, the latter mainly through shorter contact times (Padulo, Annino, D'Ottavio et al., 2013). In addition, previous research has shown the importance to stride length of the foot position relative to the centre of mass (CM) at both initial contact and toe-off (Hanley et al., 2011), notwithstanding the crucial role played by any extra distance achieved during flight. It seems logical that placing the foot too far ahead of the CM could cause too great a braking impulse for the effective maintenance of race walking speed (Lafortune, Cochrane, & Wright, 1989), and an efficient race walking technique is therefore one where the decrease in velocity during the braking phase is minimised so that the effort required to recover velocity during the propulsion phase is also reduced.

Despite the prevalence of GRF measurements in normal and pathological gait analysis, very little has been conducted in race walking. Two early studies by Fenton (1984) and Cairns, Burdette, Pisciotta, & Simon (1986) were on non-elite athletes and conducted before 1995, when the current rule governing the knee's movement was introduced. These early studies therefore do not reflect present-day elite race walking, and new research on this unique form of gait is required to describe the GRF patterns that occur in world-class athletes and to identify key kinetic variables (e.g. peak vertical loading force). Such research can aid coaches in identifying the importance of elements of high-quality race walking that normally are unavailable to them, such as braking and propulsive impulses. New research that combines GRF data with key spatiotemporal data (e.g. stride length and width) will therefore be useful to coaches who wish to have a sound empirical basis for their training practices. The purpose of this study was to describe and analyse GRF variables in world-class race walkers and relate them to key kinematic and spatiotemporal variables.

Methods

Participants

The study was approved by the Faculty Research Ethics Committee and 19 race walkers of 10 different nationalities gave written informed consent. The athletes comprised 11 men (25.8 ± 3.1 years, 1.79 ± .05 m, 66.3 ± 8.0 kg) and eight women (26.0 ± 4.2 years, 1.66 ± .05 m, 55.1 ± 4.9 kg). All participants had competed at the Olympic Games or IAAF World Championships (which was part of the inclusion criteria). All 11 men had previously competed over 20 km (personal best time: 1:23:06 ± 2:16) with nine also competing over 50 km (3:51:12 ± 8:02). The mean personal best time for the women over 20 km was 1:30:40 (± 1:48).

Data collection

Each athlete race walked along a 45 m indoor track at a speed equivalent to their season's best time for 20 km or 50 km, dependent on specialism. A national race walking coach and qualified judge were present to ensure legal race walking technique was adopted. Timing gates were placed 4 m apart around two force plates (Kistler, Winterthur) that recorded both left and right foot contact phases and any flight time. Athletes completed at least 10 trials each and the three closest to the target time (within 3%) were analysed provided there was no evidence of conscious stride adjustment when contacting the force plates. The force plates recorded at 1000 Hz and were covered with a synthetic athletic running surface so that the testing area was flush with the rest of the runway (Bezodis, Kerwin, & Salo, 2008). Synchronised high-speed video data were collected at 100 Hz (Fastec, San Diego, CA). The shutter speed was 1/500 s, the *f*-stop was set at 2.0, and there was no gain; the resolution of the camera was 1280 x 1024 pixels. The camera was placed approximately 12 m from and perpendicular to the line of walking. Extra illumination was provided by 104 kW of overhead floodlighting.

Data processing

In addition to stride width, which was measured using the centre of pressure readings from the force plates, the three components of the GRF data (vertical, anteroposterior and mediolateral) were analysed during each contact phase. Contact time was considered to begin when the vertical force trace exceeded 5 N and to end when it decreased below 5 N; flight time was calculated as the time between successive steps. To account for differences in body size, all GRF data were normalised using the athletes' weights and expressed as bodyweights (BW). Results for each individual were averaged for both contact phases over the three trials.

The video files were manually digitised by a single experienced operator to obtain kinematic data using motion analysis software (SIMI, Munich). Digitising was started at least 10 frames before the beginning of the stride and completed at least 10 frames after to provide padding during filtering (Smith, 1989). Each video was first digitised frame by frame and upon completion adjustments were made as necessary using the points over frame method (Bahamonde & Stevens, 2006). A cross-validated quintic spline was used to smooth the raw data before coordinate calculations (e.g. CM position) (Giakas & Baltzopoulos, 1997). Seventeen segment endpoints were digitised for each participant and a fourteen-segment body segment parameter model (de Leva, 1996) was used to obtain data for the CM and particular limb segments. The fourteen segments were the head, trunk, upper arms, forearms, hands, thighs, lower legs and feet.

In order to ensure reliability of the digitising process, repeated digitising (two trials) of one race walking sequence at the same sampling frequency was performed with an intervening period of 48 hours. The same three statistical methods for assessing reliability were used: 95% limits of agreement (LOA), coefficient of variation (CV) and intraclass correlation coefficient (ICC). The data for each tested variable were assessed for heteroscedasticity by plotting the standard deviations against the individual means of the two trials. If the data exhibited heteroscedasticity, a logarithmic transformation of the data ($\log_e$) was performed before the calculation of absolute reliability measures (Bland & Altman, 1986). The LOA (bias ± random error), CV and ICC (3,1) values for CM x-velocity were –0.01 ± 0.08 $m \cdot s^{-1}$, ± 0.72%, and 1.00 respectively; for CM x-coordinate –0.001 ± 0.004 m, ± 0.05%, and 1.00 respectively; for the right foot x-coordinate 0.000 ± 0.002, ± 0.03%, and 1.00 respectively; for the left foot x-coordinate –0.001 ± 0.006, ± 0.07%, and 1.00 respectively; and for knee angle –0.3 ± 1.2°, ± 0.24%, and 1.00 respectively. These results thus showed minimal systematic and random errors and confirmed the high reliability of the digitising process.

Data analysis

With regard to vertical GRF data, the variables analysed were impact peak force, loading peak force, midstance force, and push-off peak force. The impact peak was identified visually as a distinct peak occurring normally within the first 30 ms of contact. The loading peak force was identified as the next peak in the vertical GRF trace and typically occurred between 50 and 70 ms after initial contact. The midstance force value was measured at the instant where the anteroposterior force trace crossed zero (from the deceleration phase to the acceleration phase). The push-off peak force was identified as the maximum vertical force after midstance.

The two shear GRF traces were analysed in a similar fashion. The anteroposterior GRF variables chosen for analysis were the maximum magnitudes of the deceleration (‘braking’) and acceleration (‘propulsion’) forces, the duration of the braking and propulsion phases, and the resulting change in velocity values (from the calculation of both negative and positive impulses). Net change in velocity was calculated from net impulse over the whole contact phase, while the positive and negative impulses were summed to further calculate gross change in velocity. In those traces showing evidence of a brief ‘spike’ peak at initial contact, the spike impulse was calculated. In the mediolateral direction, the variables chosen were the magnitudes of the maximum lateral force (during late stance) and maximum medial force (during midstance). Early stance values have not been reported as no consistent pattern emerged during this phase. The instants during contact where the predominant lateral force became medial and then reversed back to lateral were also measured. Temporal data have been reported as normalised data using percentage of stance time.

Race walking speed was determined as the mean horizontal speed during one complete gait cycle (using the digitised data). With regard to spatiotemporal variables, stride length was measured as the distance between successive right foot contacts. Stride length was also expressed as a percentage of the participants' statures, and referred to as stride length ratio. Stride frequency was calculated as the reciprocal of stride time (Padulo, Chamari, & Ardigò, 2014). 'Foot ahead ratio' was used to describe the horizontal distance from the foot to the CM at initial contact as a proportion of stature. Similarly, 'foot behind ratio' was the horizontal distance from the foot to the CM at the final instant of contact as a proportion of stature. Flight distance was the distance the CM travelled during flight, measured from the instant of toe-off to the instant of initial contact (Hunter, Marshall, & McNair, 2004). The knee angle was calculated as the sagittal plane angle between the thigh and lower leg segments and considered to be 180° in the anatomical standing position (Hanley & Bissas, 2013; Padulo, Annino, Tihanyi et al., 2013).

Statistical analysis

All statistical analyses were conducted using SPSS Statistics 20 (IBM SPSS, Inc., Chicago, IL). Independent *t*-tests were conducted to compare values between men and women, with adjustments made if Levene's test for equality of variances was less than 0.05. One-way ANOVA was used to compare vertical force peak magnitudes, with post-hoc Tukey tests conducted (Field, 2009). Pearson's product moment correlation coefficient was used to find associations between variables; statistical significance was accepted as $p < .05$ for all tests.

Results

None of the normalised GRF or kinematic variables differed between sexes and consequently the results for both men and women have been combined for the purposes of description and analysis. The mean race walking speed during testing was 13.40 km·h^{-1} (s = .79), stride frequency was 1.61 Hz (s = .07), and stride length was 2.32 m (s = 0.17), which equated to a mean stride length ratio of 132.7% (s = 7.4). Mean contact time was 0.280 s (s = .019), while flight time was 0.031 s (s = .010); the mean flight distance during this phase was 0.12 m (s = .05). The mean foot ahead ratio was 21.4% (s = 1.7) and the mean foot behind ratio was 27.0% (s = 1.2). The mean knee angle at contact was 180° (s = 3), hyperextending to 185° (s = 4) at midstance and flexing to 148° (s = 4) at toe-off. The mean stride width was .048 m (s = .037). Race walking speed was positively correlated with stride length ratio (r = .71, p = .001), flight time (r = .46, p = .049) and flight distance (r = .69, p = .001), while longer foot behind ratios and flight distances were associated with longer stride length ratios (r = .49, p = .034 and r = .56, p = .013 respectively). During the braking phase of contact, the mean decrease in velocity was –0.58 km·h^{-1} (s = .10) while the mean increase in velocity during the propulsive phase was 0.71 km·h^{-1} (s = .11), for a net change in velocity of 0.14 km·h^{-1} (s = .11) and gross change in velocity of 1.29 km·h^{-1} (s = .17). Higher stride frequencies were associated with smaller gross changes in velocity (r = –.46, p = .046) and shorter contact times (r = –.86, p < .001), but not with shorter flight times (r = .30, p = .21).

The values for key kinetic variables and the timing of their occurrence are shown in Table 1 below, and a diagram of the averaged race walk GRF trace is shown in Figure 1. In the vertical direction, a distinct impact peak was identified in the traces of 15 of the 19 participants. Longer flight times were associated with both higher loading peak forces (r = .47, p = .042) and higher midstance forces (r = .51, p = .025). In the anteroposterior direction, a brief spike impulse that began at initial contact and lasted 20 ms (*s* = 3) was identified in the traces of 18 participants. The braking phase lasted 41.0% (*s* = 5.5) of total stance time; its duration was correlated with foot ahead ratio (*r* = .53, *p* = .020), and there was a relationship between gross change in velocity and peak braking force (*r* = .54, *p* = .016) but not with braking phase duration. By contrast, during the propulsive phase both greater maximum propulsive forces and longer propulsive phases were associated with larger gross changes in velocity (*r* = .61, *p* = .005 and *r* = .59, *p* = .008 respectively). Later peak propulsive forces were associated with longer flight times (*r* = .49, *p* = .035), while higher midstance forces were correlated with smaller gross changes in velocity (*r* = –.68, *p* = .001).

In early stance, the athletes differed in their experiences of mediolateral forces (some were predominantly medial, others lateral, and others experienced both). There was however a distinctive pattern of medially-directed forces lasting from 28.6% (*s* = 6.1) to 61.3% (*s* = 5.0) of total stance time, after which laterally-directed forces were observed until toe-off. Faster walkers took longer to reach the medial peak force (*r* = .61, *p* = .006), and narrower stride widths were associated with smaller medial peaks during midstance (*r* = .63, *p* = .007), smaller vertical push-off peak forces (*r* = .60, *p* = .011), smaller braking peak forces (*r* = .60, *p* = .011), and smaller propulsive peak forces (*r* = .49, *p* = .046).

Discussion

The aim of this study was to describe and analyse GRF variables in world-class race walkers and relate them to key spatiotemporal variables. It was informative that no differences between sexes were found for GRF variables or the few kinematic variables when normalised. Previous research has found that elite men were faster than elite women because of longer step lengths, and this difference was in turn largely due to men's greater statures, rather than joint angular differences or movement patterns (e.g. there was no difference in step frequency) (Hanley et al., 2013). The results of the present study likewise suggest that elite male and female race walkers have comparable motions as a result of similarly well-developed techniques that optimise performance. Even though the athletes race walked at competitive rather than maximal speeds, it was still noticeable that faster walkers had longer stride lengths and flight distances. This was because very brief but non-visible flight periods were recorded for all athletes (and indeed are commonplace in competition (Hanley et al., 2011; Knicker & Loch, 1990)). Although longer flight distances were clearly advantageous to this group of athletes, it is not advisable for race walkers to deliberately increase flight time when attempting to walk faster as this also increases the risk of disqualification. The best advice might therefore be to try to maximise flight distance with the minimum of flight time (i.e. avoid upward rather than forward movement), and it was interesting in this study that these two temporal variables did not always correlate with the same GRF or kinematic variables. Coaches should monitor their athletes for visible loss of contact and develop sound techniques in training to prevent it.

Race walking is an abnormal form of gait and while all peak forces were higher than those typically found in normal walking (Levine, Richards, & Whittle, 2012), what was particularly striking was how the vertical trace did not increase after midstance with the result that the push-off peak was approximately 83% of the earlier loading peak. The corresponding kinematic data suggest that the reduction in vertical force during late stance is a result of the knee's movement from hyperextension in midstance to flexion during late stance, and means that the race walker's CM has a flat trajectory that does not follow a pendulum-like gait as in normal walking (Pavei, Cazzola, La Torre, & Minetti, 2014). Instead, the trajectory during race walking is vertically lower than in normal walking (less of a circular arc) and thus means that it is dynamically more similar to running (Pavei et al., 2014). Comparable GRF results were found in non-elite race walkers by Fenton (1984) and this similarity might be because those race walkers had to fully extend the knee by midstance (but not at initial contact) even before the current rule was introduced in 1995 (although the knee's movement was not measured by Fenton (1984)). The knee's kinematics before toe-off might therefore prove to be useful in reducing vertical propulsion of the CM, and reveal a previously unheralded advantage of the straightened knee to efficient race walking that helps prevent visible loss of contact, and further highlights the value of excellent technique.

As endurance athletes, it is important for race walkers to reduce overall movement inefficiency and some features of the vertical GRF pattern (e.g. the slight flattening of its stance profile) might be an attempt to reduce vertical displacement and conserve mechanical energy (Murray, Guten, Mollinger, & Gardner, 1983). Nearly all athletes experienced a brief propulsive impulse at initial contact that theoretically should have reduced the magnitude of force production in late stance (Lafortune et al., 1989), but its very small size meant that no such association was found. However, greater force magnitudes at midstance were associated with less gross change in velocity, showing that the flatter vertical GRF trace already described was also beneficial in reducing fluctuations in velocity during stance. This was particularly important as athletes who experienced larger gross changes in velocity experienced longer contact times and thus had lower stride frequencies. While net change in velocity during stance was by necessity positive (at 0.14 $km \cdot h^{-1}$) because of the inevitable slowing down that occurs during flight, the key to requiring smaller increases in velocity during late stance is to have experienced smaller decreases in velocity during early stance. Achieving this was associated with smaller peak braking and propulsive forces (rather than the duration of these phases) that in turn were achieved with narrower stride widths. By contrast, coaching advice that the foot ahead distance should be kept very short (Summers, 1991) was not strongly supported by this study as it was not associated with decrease in velocity (or peak braking force) during early stance. This was possibly because the athletes in this study were well-trained, elite athletes whose foot positioning was optimised at just over 20% of stature, a similar value to that found in world-class competition (Hanley et al., 2011), and thus a useful guide for athletes to avoid overstriding.

Although there were no phases of double support identified in any of the race walkers' traces, lateral forces were still experienced during early and late stance (as in normal walking where double support does occur). Relatively large medial forces were recorded in all athletes for roughly the middle third of stance; as suggested by previous research (Murray et al., 1983), this was possibly due to an acceleration of the CM towards the swing side of the body as a result of pelvic obliquity that occurs to reduce the CM's vertical displacement in the absence of knee flexion. The medial force peak was smaller in those athletes with a narrower stride width, and suggests that walking in a straighter line necessitates less lateral movement to maintain balance, and a reduction in muscular energy requirements is achieved (Levine et al., 2012). In addition, athletes with narrower stride widths did not have to produce as much force in the vertical and anteroposterior directions during late stance, and this might also show a reduced need for energy expenditure. A narrow stride width has been proposed by race walk coaches for some time (e.g. Markham, 1989) as a means of increasing stride length (there was no association in this study) but these results show that it might have other benefits. As the medial peak force timing was correlated with race walking speed, the race walker's effectiveness in delaying the medial motion of the CM in midstance might be a feature of better race walking (through better postural control, for example). The lateral forces experienced during late stance appeared to be an attempt to reverse the pelvic obliquity movement before contralateral initial contact (Murray et al., 1983). These features of both medial and lateral GRFs suggest there is a requirement for race walkers to develop the pelvic muscles involved (e.g. gluteus medius) so that CM movement efficiency is improved.

A main strength of the present study was the fact that all athletes had competed at the highest standard of international competition. However, this meant that the sample size was restricted because of the difficulty of recruiting such high-standard athletes. With regard to other limitations, future studies could adopt three-dimensional kinematic measurements that would allow for the analysis of the CM's movement in all three planes (e.g. Pavei et al., 2014) as the two-dimensional analysis undertaken in this study did not allow for appreciation of the effects of lateral movement. In addition, direct measurements of the CM in race walking might be more suitable than using body segment parameter data because of the unusual gait adopted (Pavei, Cazzola, & Minetti, 2012), especially if a greater number of kinematic variables is being studied.

Conclusion

This study was the first to describe and analyse important aspects of GRF traces in world-class race walkers. Race walking is an abnormal form of gait with a GRF profile different from normal walking, not just in terms of force magnitudes, but also in appearance. This was especially true of the vertical GRF pattern, but there were also elements of the anteroposterior and mediolateral forces that were evidence of efforts to optimise efficiency. The results of this study have some practical implications for race walkers and their coaches. First, the knee's abnormal movement from hyperextension to flexion in race walking seems to restrict upward propulsion at toe-off that might help prevent visible loss of contact (although brief, non-visible flight is beneficial). Second, placing the foot ahead of the body need not be overly detrimental with regard to braking forces, provided its length is about 20% of stature; in addition, a narrow stride width is advantageous to the athlete. Finally, the large mediolateral forces that occur are a response to the straightened knee and could demonstrate the need for appropriate training of pelvis-stabilising muscles such as gluteus medius.

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Figure legends

Figure 1. An averaged GRF trace of the race walking stance phase (left foot) with vertical, anteroposterior and mediolateral components shown.

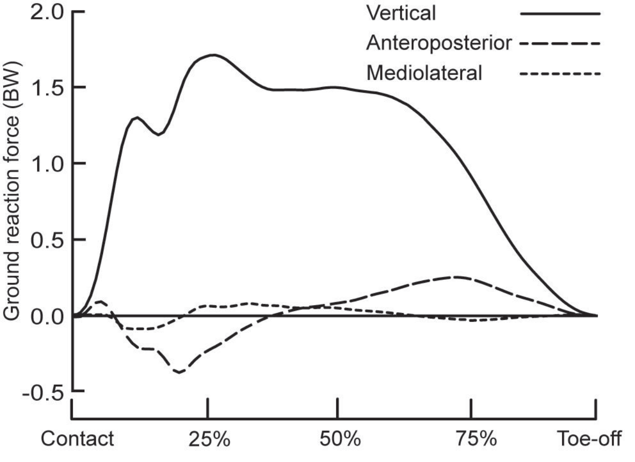
Vertical
Anteroposterior
Mediolateral
Ground reaction force (BW)
2.0
1.5
1.0
0.5
0.0
-0.5
Contact
25%
50%
75%
Toe-off

Table I. Mean (± *s*) peak values for GRF variables and their timing during race walking.

	Peak values (BW)	Timing (% of stance time)
Vertical direction		
Impact force	1.30 (± .18)[a]	16.4 (± 4.3)
Loading force	1.72 (± .18)[a]	23.5 (± 4.1)
Midstance force	1.55 (± .12)[a]	41.0 (± 5.5)
Push-off force	1.43 (± .09)[a]	58.0 (± 6.2)
Anteroposterior direction		
Braking force	–0.36 (± .08)	16.8 (± 2.8)
Propulsive force	0.23 (± .03)	75.4 (± 2.5)
Mediolateral direction		
Medial force	0.11 (± .05)	41.7 (± 5.4)
Lateral force	0.06 (± .03)	74.3 (± 4.3)

[a]The peak vertical loading force was significantly larger than the impact, midstance and push-off peak forces ($p < .001$).