KINEMATICS OF RACE WALKING

Sally J. Phillips
Department of Physical Education
University of Maryland
College Park, MD 20742 USA

Jody L. Jensen

The race walker exhibits a movement pattern classified within the category of upright locomotion. As such, race walking has numerous similarities to other locomotor acts, yet retains its own uniqueness. The cyclical motion of the lower extremity in skilled locomotor performance must be controlled by an automated underlying motor program so that minimal variation occurs across repetitive cycles. It is conceivable that a single theory could account for the gait patterns of walking, race walking and running; however, we need to expand our knowledge of race walking kinematics and kinetics before such a unifying theory can be posited. Despite the similarities with both walking and running, race walking has simply not been the subject of equal investigative interest. We know little of the kinematic parameters of the race walking technique beyond qualitative descriptions (Marchetti, Cappozzo, Figura and Felici, 1982; Kitchen, 1981; Elson, 1967) and coaches' recommendations (Hopkins, 1978; Arnold, 1980). From a purely practical standpoint, the lack of quantitative, biomechanical data concerning this Olympic sport is somewhat surprising. Thus, the purpose of this initial investigation is to quantify selected kinematic features of elite race walking performance in order to lay the foundation for future practical and theoretical work.

Walking, by definition, includes a period of double support during each complete cycle or stated negatively, at no time are both feet simultaneously off the ground. Competitive race walking is indeed a specialized form of walking since this absence of a flight phase is one of the major rules of the sport. Violation of this rule is called lifting, and competitors may be disqualified for infractions of the rule. The race walker is also required to achieve a fully extended knee of the support leg as the body center of mass passes through the vertical. To meet these requirements, certain techniques have become standard. Upon heelstrike, the leading leg is already extended at the knee. Force platform records presented by Payne (1978) indicated a 63% increase in vertical forces at heelstrike when comparing normal walking to race walking. The double knee lock sequence evident in normal walking during the stance phase is not present in race walking, elminінating knee extension as a propulsive mechanism. Knee flexion cannot occur until after the body passes the vertical position.

Despite the definitional similarities between walking and race walking, the speeds achieved by the competitive race walker in the Olympic distances of 20km and 50 km are closer to that of running than walking. Many "average" runners have experienced embarrassment as the highly trained race walker passes by at a 7 minute per mile pace. When compared to running, the technique demands of race walking do not allow for the greatest efficiency in terms of either mechanical energy utilization or metabolic costs (Marchetti, Cappozzo, Figura and Felici, 1983). Likewise, the external work per unit distance is greater for race walking than walking at speeds above 6-7 km·hr^{-1} (Cavagna and Franzetti, 1981). Nonetheless, race walkers are highly trained endurance athletes. With the exception of a slightly lower aerobic capacity, the physiological profile of the race walker was found to be comparable to that of the marathon runner and other elite endurance performers (Franklin, Kaimel, Moir and Hellerstein, 1981; Hagberg and Coyle, 1983). In fact, Franklin and his colleagues suggested that successful race walking performance may depend more on technique, motivation and efficiency than on extremely high levels of aerobic capacity. Therefore, it was the movement pattern of elite race walkers, as reflected by kinematic variables, which became the major focus of this paper.

METHODS

Three elite male race walkers were filmed outdoors using a 16mm, pin-registered Photosonics camera operating at a sampling rate of 115 fps. Each subject was nationally ranked within the top 10 for the 50km race, although Subject 3 preferred longer races (100 km). Anthropometric characteristics of the subjects are reported in Table 1. After sufficient warm-up, which exceeded 30 minutes per subject, each walker was filmed 5 times from the sagittal viewpoint followed by 4 trials of frontal plane movements. The camera was fitted with a 25 mm lens and an exposure time of 1/800 seconds was used. Subjects were asked to simulate a comfortable, yet "optimum " race pace.

Table 1

RELEVANT ANTHROPOMETRIC DATA

Subject	1(VO)	2(SV)	3(AP)
Height(cm)	199	195	172
Weight (kg)	78.7	77.2	64.9
Thigh (cm)	48.0	43.5	38.0
Shank (cm)	48.0	48.8	44.5
Pelvis (cm) (Crest to trochanter)	14.0	17.0	15.0
Knee Hyperextension (degrees)	7.0	10.0	10.0
Age (year)	25.3	26.7	35.4
Experience (years)	6.0	6.0	8.0

The processed film was viewed with a Lafayette Analyzer using a rear projection system which magnified the film image 75X. Data reduction was accomplished with a Numonics digitizing system, interfaced with a Univac 1140 computer. After determining the temporal characteristics of all 15 trials (sagittal view), 6 trials were selected for further analysis. Joint centers or body landmarks for each frame during an entire cycle were digitized in the following order: metatarsophalangeal joint, lateral malleolus, knee joint center, hip joint center, superior iliac crest, spinous process of seventh cervical vertebra and elbow joint center. Due to obvious independent motion of the shoulder girdle and possible trunk rotation about the vertical axis, C7 was found to give a better representation of the trunk segment than the shoulder joint center. Digitized data were smoothed second order, recursive Butterworth filter with a cut-off frequency of 9 Hz.

RESULTS AND DISCUSSION

Temporal-Distance Characteristics.

Subject 1 consistently demonstrated faster race walking velocities ($\bar{X} = 5.16$ m·s^{-1}) than the other two subjects (Table 2). Each subject was relatively consistent across his own 5 trials. Subject 1 also had the longest step length (right heel to right heel), even when expressed as a multiple of total height (1.61). This race walker also had the shortest cycle time (565ms in Trial 1). Cycle times of Subject 2 were the longest ($\bar{X}$ = 636ms). The fastest velocity, greatest stride length and shortest cycle time for each subject are indicated in Table 2 with an asterisk. Subject 3 achieved slightly greater velocities than Subject 2 despite a shorter stride length. The greater frequency (shorter cycle time) may be anticipated in light of the subject's shorter stature. An illegal flight phase was observed in all trials, but it is doubtful if even the longest flight time of 52ms could be detected by the human eye. The 6 trials selected for further analysis are also identified in Table 2.

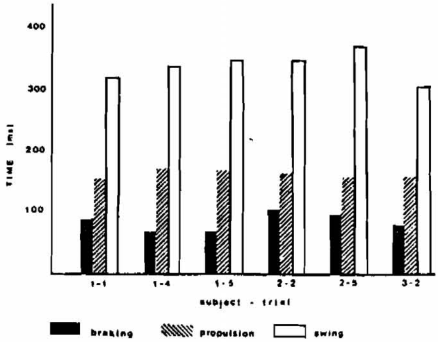

Figure 1. Temporal Data of Race Walking Across Trials

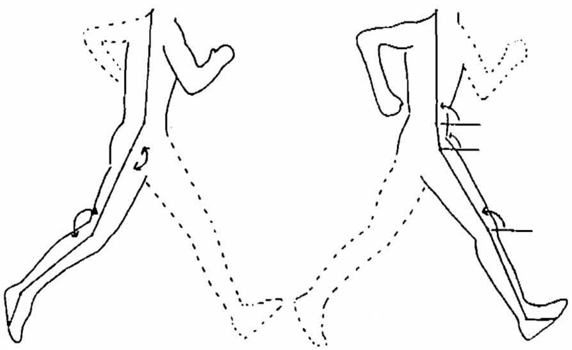

Figure 2. Typical Angular Positions at Takeoff and Heelstrike

The complete cycle can be temporally partitioned in numerous ways. The swing phase consumed an average of 58%, 56% and 55% respectively for the three race walkers, averaged across 5 trials per subject. The greatest swing percentage was exhibited by the walker with the greatest velocity. Swing phase percentages greater than 50% might be anticipated in light of the illegal flight phase. Intrasubject variation for both the swing and stance phases was within 20ms.

We further subdivided the stance into braking and propulsive phases based on the position of the laberal malleolus relative to the hip joint center. If the hip was in front of the ankle, this was classified as the propulsive phase. This assumption appeared plausible since trunk movement was minimal and the arms were synchronized in opposition. In addition, force records presented by Payne (1978) appear to support the legitimacy of this conclusion. For the 6 trials examined, the propulsive phase was considerably longer than the braking phase (Figure 1). In trials 4 and 5 for Subject 1 the propulsive phase consumed 71.4% of the total stance time, with only 70ms

Table 2

DESCRIPTIVE CHARACTERISTICS OF REPEATED TRIALS

	Velocity $(m \cdot s^{-1}/k \cdot h^{-1})$	Step Length (m/hgt.)	Cycle Time (ms)	Flight Time (ms)
Subject 1(VO)				
Trial 1*	5.18/18.65	2.93/1.47	565[c]	52
2	4.97/17.92	2.94/1.48	591	52
3	4.97/17.90	3.03/1.52	609	44
4*	5.49/19.78[a]	3.20/1.61[b]	582	52
5*	5.15/18.54	3.04/1.53	591	52
Mean	5.16/18.56	3.03/1.52	588	50
Subject 2(SV)				
Trial 1	4.28/15.40	2.79/1.43	652	17
2*	4.70/16.91[a]	2.90/1.49[b]	617[c]	35
3	4.43/15.93	2.89/1.48	652	35
4	4.30/15.50	2.77/1.42	643	17
5*	4.67/16.82	2.88/1.48	617[c]	52
Mean	4.48/16.11	2.85/1.46	636	31
Subject 3(AP)				
Trial 1	4.61/16.60	2.57/1.49	557	35
2*	4.90/17.65[a]	2.64/1.54[b]	539[c]	35
3	4.51/16.25	2.59/1.51	574	26
4	4.28/15.40	2.49/1.45	583	17
5	4.20/15.11	2.52/1.46	600	17
Mean	4.50/16.20	2.56/1.49	571	26

* Trials selected for further analysis
a Fastest within-subject trial
b Longest step length (within-subject)
c Shortest cycle time (within-subject)

spent in braking. The shortest relative propulsive phase was 61.3% exhibited by Subject 2 in Trial 2.

Angular Positions at Takeoff and Heelstrike.

Typical body configurations at takeoff and heelstrike are shown in Figure 2 along with the conventions used to measure the segmental and intersegmental angles. At takeoff the trunk was inclined slightly forward of the vertical in all 6 trials ($\overline{X} = 85.2^\circ$, range (R) = 5.8°) as was the pelvic girdle ($\overline{X} = 67.4^\circ$, R = 2.6°). The trunk was rotated to the left as the right foot pushed off the ground and the left humerus was nearly horizontal. The hip was near full extension ($\overline{X} = 178.6^\circ$, R = 4.6°). Neglecting the one trial by the third subject, the mean hip extension was 179.2 degrees with a range of 2.0 degrees. The thigh inclination averaged 68.8 degrees (R = 3.7°), and the shank inclination was 36.2 degrees. The knee was not fully extended at takeoff ($\overline{X} = 147.5^\circ$, R = 7.6°).

At heelstrike, the ankle joint was plantarflexed and the knee was fully extended ($\overline{X} = 181.5^\circ$, R = 10.6°). The second subject exhibited almost 8 degrees of knee hyperextension at heelstrike. The thigh inclination averaged 109 degrees (R = 6.7°), and the hip was slightly flexed ($\overline{X} = 162.8^\circ$, R = 11.1°). The pelvis at heelstrike was inclined backward of the vertical a maximum of 7 degrees for Subjects 1 and 3, while Subject 2 had the pelvic girdle in a position of slight forward inclination (4 degrees). Only Subject 3 had the trunk inclined slightly backward at heelstrike ($\overline{X} = 86.5^\circ$, R = 8.1° for all trials analyzed).

Thigh-knee Range of Motion (sagittal plane).

Based on the average of 6 trials, the thigh segment was maximally rotated 40.4 degrees forward of the vertical (drawn at hip joint center) in mid to late swing (R = 8.3°), and 27.3° behind the vertical (rotated backward) in late stance (R = 4.2°). Average maximum knee flexion of 100.7° occurred during mid-swing, and maximum knee extension of 189.1° was evident during mid-stance. All subjects demonstrated knee hyperextension during stance.

Angle-angle diagrams were constructed to examine the interrelationship of thigh and knee motion and the associated variability both between subjects and within a single subject. When comparing Trials 4 and 5 (fastest walking speeds) for Subject 1 (Figure 3), no difference during the stance phase was noted including the position at heelstrike and takeoff. This might be anticipated since the times of the braking and propulsive phases during stance were identical. The Subject exhibited slightly greater knee flexion (4 degrees) during the swing phase of the fastest trial (swing phase 8ms shorter). Since the thigh motion was virtually identical in the two trials, the differences in the intersegmental knee angles were due to greater shank ranges of motion. The larger range was associated with the larger step length and the faster horizontal velocity. Trial 1 (not shown) resulted in a swing pattern graphically between the two trials presented. The consistency of motion demonstrated by this elite rate walker was remarkable.

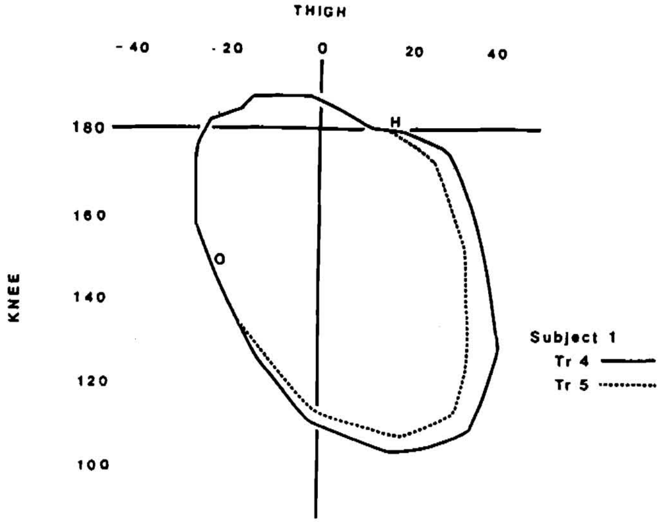

Figure 3. Angular Relationship of Thigh and Knee for Subject 1 (H = heelstrike, O = takeoff)

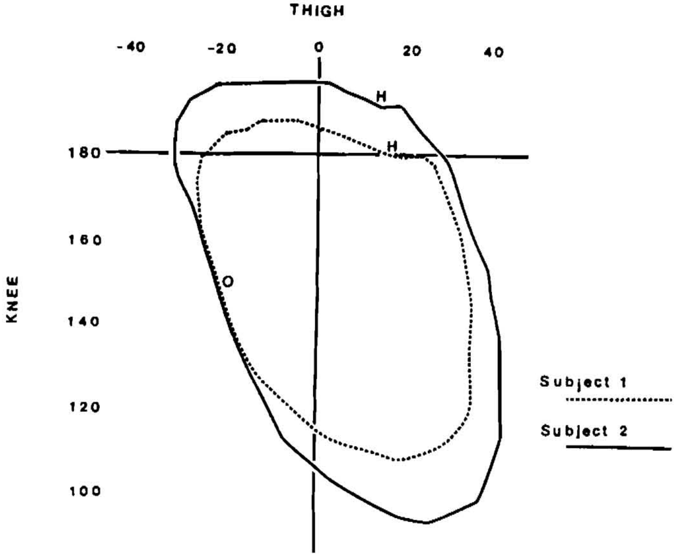

Figure 4. Between-Subject Comparison of Thigh and Knee Angular Relationships

We also compared the fastest trial of Subjects 1 and 2 (Figure 4). Subject 2 exhibited greater ranges of motion at both the knee and thigh. The takeoff position of both athletes were similar, but knee hyperextension at heelstrike was greater for Subject 2 due to greater forward rotation of the shank. Differences in the swing phase may be related to differences in the thigh/shank ratios of the two subjects. Although total stature was similar, Subject 2 had a relatively longer shank than thigh, whereas the segment lengths were equal for Subject 1. Despite comparable flight times, the cycle time was longer for Subject 2 (greater ROM) even though the stride length was somewhat shorter when contrasted with Subject 1.

Sagittal Plane Motion of Trunk and Pelvis.

In most cases, the angular motion of the trunk segment in the sagittal plane was minimal. With the exception of one trial, the total range of trunk angular motion was less than 10 degrees (Table 3). The maximum forward lean of the trunk occurred at different points in time for the three subjects.

Table 3

RANGES OF ANGULAR MOTION IN SAGITTAL PLANE
(Degrees with respect to vertical)

Trial	Trunk			Pelvic Tilt		
	Forward	Backward	Range	Forward	Backward	Range
1-1	9.9	-3.6	6.3	24.8	6.6	31.4
1-4	8.1	0.1	9.0	25.3	10.9	36.2
1-5	7.2	-0.7	6.5	25.0	7.6	32.6
2-2	12.6	-19.8	32.4	27.5	3.5	31.0
2-5	14.5	-5.8	8.7	28.8	2.9	31.7
3-2	1.2	3.3	4.5	28.4	14.0	42.4
$\bar{X}$	8.92	2.16	11.2	26.6	7.6	34.2
R	13.3	25.6	27.9	4.0	11.1	11.4

The fastest walker, Subject 1, exhibited maximum forward lean of 7 to 10 degrees (with respect to the vertical) during the mid to late stance. Greater forward lean of 12 to 15 degrees was demonstrated by Subject 2 during early and mid stance. Subject 3 remained virtually upright with less than 1.5 degrees change during stance. Backward leaning of the trunk did not occur in 3 of 6 trials examined (indicated in Table 3 by a negative value). The maximum values for trunk rotation in a CW (backward) direction occurred at or near heelstrike for Subjects 1 and 3. Subject 2 exhibited an unusual backward trunk lean of 19.8 degrees during the swing phase in Trial 2. However, in Trial 5 there was a less than 1° change during the swing cycle. A visual re-examination of the film record did not confirm the backward lean, but rather pointed to a measurement problem due to the three-dimensional motion. The pelvic girdle had rotated about a vertical axis such that the linear position of the iliac crest was forward of the general line of the trunk. Therefore, pelvic rotation in the horizontal plane was confirmed as opposed to a backward lean. Since backward trunk lean was minimal in all other trials, the rotation of the pelvic girdle about a vertical axis was assumed to be minimal.

Ranges of motion for pelvic tilting in the sagittal plane were greater than trunk ranges of motion, but in many ways pelvic tilting was more consistent across subjects. The total range varied from 31.0 to 42.4 degrees. Subject 3 with the least trunk angular range had the greatest pelvic tilt range. Maximum forward tilt of the pelvic girdle ($\overline{X} = 26.8^{\circ}$) occurred late in the stance phase. For subjects 1 and 3, maximum forward tilt occurred 35ms prior to takeoff; for Subject 2 it occurred up to 80ms earlier. Maximum backward tilt of the pelvic girdle (2.9 to 14.0 degrees) typically occurred during the swing phase, 61 to 87ms prior to heelstrike. These values must be interpreted with some caution in cases where pelvic rotation about a vertical axis was occurring simultaneously.

Lateral Tilt.

During the stance phase the iliac crest of the stance leg was vertically elevated and the iliac crest of the swing leg was lowered. As viewed from either the anterior or posterior (Figure 5) the magnitude of the lateral pelvic tilt with respect to the horizontal was within the range of 13 to 20 degrees. Variation in this parameter across subjects was noted, with Subject 2 exhibiting the greatest lateral pelvic tilt. Compensatory reactions to the lateral pelvic tilt occurred at the shoulder girdle and within the vertebral column. As the pelvis on the stance leg vertically raised, the shoulder on the same side appeared to drop vertically. A temporary scoliatic (lateral) curvature of the vertebral column resulted. Subject 2 with the greatest lateral pelvic tilt also exhibited the more severe scoliatic curve.

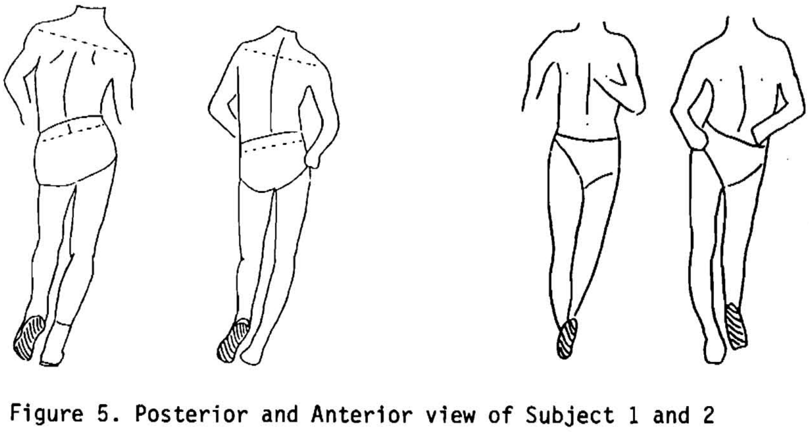

Figure 5. Posterior and Anterior view of Subject 1 and 2

Vertical displacement of the superior iliac crest was quantified from the sagittal view of the film records. Upon impact, the iliac crest lowered slightly then raised vertically during the majority of the stance phase. In the swing phase the highest elevations were near takeoff and heelstrike. The iliac crest of the swing leg reached its lowest point during mid-swing. For the entire cycle of a single lower extremity, the mean total vertical displacement of the iliac crest was 8.6 cm. This implied an average 4.3 cm upward displacement during stance and a downward displacement of equal value during swing. Subjects 2 and 3 exhibited total vertical displacement exceeding 9 cm whereas the maximum values for Subject 1 did not exceed 8 cm.

Other Observations.

From the anterior and posterior views of the race walkers, it was obvious that successive footfalls tended to be in a straight line of progression for all 3 subjects. This may be facilitated by the elevated pelvis position and the appearance of lateral bowing of the lower extremity on the support side. However, the lateral bowing occurred to the greatest extent just after heelstrike. Foot plant appeared to involve lateral heelstrike and rolling to the outside of the foot before returning to the midline position for flat stance. It was posited that this may be a part of the force absorption mechanism since knee flexion was not used for this purpose.

We also observed the compensatory and active motion of the upper extremities during race walking. Accurate quantitative data were not available due to apparent shoulder girdle movements. However, relative measures (from C7 to the elbow) indicated a total range of shoulder flexion-extension approximating 115 degrees. Maximum forward rotation of the right upper arm about the shoulder axis occurred just prior to takeoff of the right foot (see Figure 2). During the swing phase of the right lower extremity, right shoulder extension-hyperextension occurred, reaching its maximum backward position at takeoff of the contralateral foot. The range of motion was much greater in the backward direction than in the forward direction, indicative of purposeful muscular involvement rather than simply pendular reactions to lower extremity movements.

SUMMARY

Quantitative data concerning selected angular and linear kinematics of the racewalking motion have been reported. Walking speeds exhibited by all 3 elite race walkers were faster than those commonly reported in the scientific literature. The fastest walker exhibited remarkable consistency across repeated trials. Kinematic differences between subjects, and therefore optimum technique, may be related, in part, to individual anthropometric characteristics and joint mobility. Additional investigations involving other elite racewalkers will be necessary before practical or theoretical conclusions can be drawn.

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