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Kinematic and electromyographic patterns of Olympic race walkers

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ABSTRACT

The performance of two Olympic race walkers was studied during free-speed, fast, and race walking. Measurements of the stride and temporal components of gait, as well as the simultaneous displacement patterns of the body segments, and the electromyographic activity of muscles of the trunk and upper and lower limbs were recorded during the three walking speeds. During the testing, the race walkers achieved an average speed of 12.5 km/hr as compared to the 8.7 km/hr average speed achieved by normal men of the same age during fast walking. Race walking was characterized by an increase in cadence and stride length beyond that of normal controls (in a prior study) during fast walking, with stride lengths averaging 125% of stature during race walking, and 115% during normal fast walking. In the two race walkers the amplitudes of most of the movement patterns of the trunk and upper and lower limbs were exaggerated during race walking as compared to normal controls' fast walking. Several mechanisms were used by the race walkers to minimize the vertical excursion of the center of gravity of the body during race walking. All of the muscles monitored in the race walkers showed an increase in the amplitude of electromyographic activity during race walking as compared to fast walking; duration of muscle activity was also usually increased during race walking. Several suggestions for prevention of injuries associated with race walking are made.

The International Amateur Athletic Federation's definition of race walking stipulates that during race walking, the advancing foot must make contact with the ground before the rear foot leaves the ground and the knee of the supporting limb must be straight when that limb is in the vertical upright position.[3]

Race walkers are able to walk considerably faster than the average 5.4 mph (8.7 km/hr) fast walking speed which we found in a previous study that identified mechanisms persons use to increase from a free or comfortable speed to a fast speed of walking.[7] The purpose of this study is to identify the changes in movement patterns and muscle activity which occurred when two skilled race walkers increased from a fast speed to a race speed. We believe this information will help provide a scientific basis for training techniques for race walkers.

METHODS

The two men studied were World Class Race Walkers. Both qualified for Olympic trials and Subject 1 was a member of a recent US Olympic race walking team. One athlete was 24-years-old, 185 cm in height, and weighed 66 kgs; the other was 23-years-old, 192 cm in height, and weighed 70 kgs.

The men were photographed in our laboratory during free-speed, fast, and race walking using interrupted-light photography at 20 exposures/sec.[6] Measurements of the simultaneous displacement of targeted body parts were made from the resultant photographs. In addition, mass centers of the body segments were targeted according to Dempster[1] and measurements of their positions were made from movie film (sagittal views at 128 frames/sec and frontal views at 64 frames/sec) in order to calculate the excursion of the center of gravity of the body. The movie film was also used to measure displacements which could not be made by the interrupted-light technique.

The race walking kinematic data of the athletes (average values from two representative trials at race speed) were compared to the fast walking kinematic data of normal† men 20 to 25 years of age.[5, 7, 8]

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† Hereafter "normal" refers to data reported in prior studies 5, 7, and 8.

Surface electrodes were used to record the electromyographic (EMG) activity of major muscle groups in the lower limbs of both athletes and some major muscle groups in the upper limb and trunk of one athlete. Raw signals of all muscles were recorded simultaneously with foot-floor contact signals from our electronic walkway[2] on a light-beam recording oscillograph (frequency response, 5000 Hz). Full-wave rectified signals were also recorded for the muscles of the lower limb. Electrodes were not moved during the test. Mean values for stance, swing, and double-limb-support durations were measured from the oscillograph records.

The raw signals of all muscle groups were studied qualitatively in order to identify changes in the amplitude, duration, or pattern of activity between fast and race walking. When available, the full-wave rectified signals, rather than the raw signals, are presented in this paper to illustrate the speed-related changes in muscle activity.

RESULTS

The mean stride dimensions and temporal components of the two athletes during race walking are compared to those of normal men during fast walking[5, 7, 8] in Table 1. As compared to the men walking fast, the race walkers had a faster cadence, longer and slightly narrower strides, and less out-toeing. In the race walkers the duration of the stance phase decreased and the duration of the swing phase increased so that the stance and swing phases became nearly equal. The double-limb-support periods shortened to approximately 0.01 second (Fig. 1). Occasionally the electronic walkway records showed a brief period of floating instead of double-limb support. These floats were usually imperceptible to visual scrutiny and measured less than 0.005 second on the oscillograph records.

Sagittal rotation of the ankle, knee, and hip

Figure 2 shows the mean patterns of sagittal rotation of the ankle, knee, and hip of each athlete during a race walking cycle as compared to those of normal men during fast walking. The cycle is the time between successive instants of initial floor contact of the same foot.

As compared to normal fast walking, the ankle of the race walker was in less dorsiflexion during the stance phase and

TABLE 1
Mean stride dimensions and temporal components during race walking

Gait components	Normal men at fast speed (Mean ± 1 SD)	Subject 1	Subject 2
Velocity (cm/sec)	243 ± 19	325	344
Velocity (km/hr)	8.7 ± 0.7	11.7	12.4
Walking cycle duration (sec)	0.84 ± 0.04	0.69	0.72
Cadence (steps/min)	143 ± 6	174	166
Stride length (cm)	202 ± 15	224	248
Stride length (% height)	115 ± 8	121	129
Stride width (cm)	10.0 ± 5.2	9.2	6.5
Foot angle (degree)	5.0 ± 6.0	2	−6[a]

[a] Negative value denotes in-toeing.

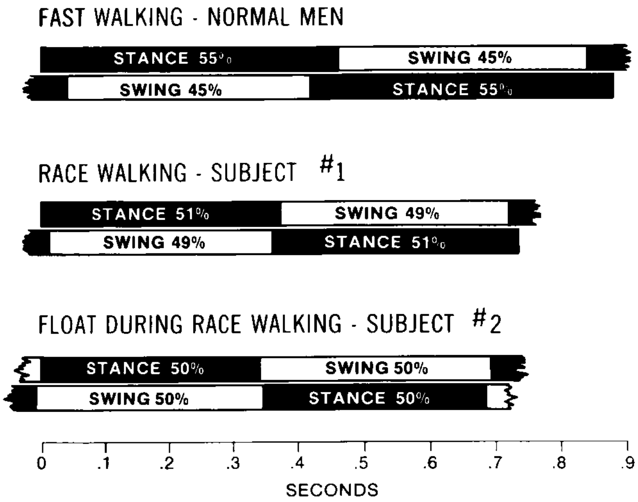

Figure 1. Average durations of the stance and swing phases (in percent of the walking cycle durations) for normal men during fast walking and for the athletes during race walking. Periods of floating, less than 0.005 second in duration, were occasionally detected by the electronic walkway.

more dorsiflexion at heel strike and during the swing phase. The normal yielding wave of knee flexion in early stance (Fl_1) was either diminished (Subject 2) or absent (Subject 1) in the race walkers. In addition, at midstance (Ex_1), the race walkers hyperextended the knee an average of 9°, while the normal men averaged 1° flexion. The peak knee flexion during early swing (Fl_2) was slightly greater during race walking than fast walking. The race walkers used much more hip flexion during the swing phase than did the normal men walking fast. After reaching that peak of hip flexion, the race walkers reversed into hip extension immediately, in contrast to the gradual reversal found during fast walking (Fig. 2).

Pelvic and trunk motion

The amplitude of the total excursion of anterior-posterior pelvic tilting in the sagittal plane during race walking was within the range of variability for normal fast walking (6.3 ± 2.2°, where 2.2° equals one SD). Race Walker 1 used 5.7° and Race Walker 2, 8.5°.

Pelvic rotation in the transverse plane averaged 23 ± 6° during normal fast walking and increased to 44° during race walking. Rotation of the thorax in the transverse plane also doubled from the normal fast walking average of 10 ± 3° to 20° during race speed.

Measurements of frontal plane pelvic tilting for Subject 2 during fast walking were used as the control data for this gait component. During fast walking, he used an excursion of 12° of frontal plane tilt, notably less than the average total excursion of 28° for both athletes. With the alternating periods of single-limb support during race walking, the pelvis on the supportive side rotated to its highest point, and the pelvis of the swinging side rotated to its lowest point (Fig. 3); the torso laterally flexed toward the supportive limb and the cervical spine laterally flexed away from the supportive

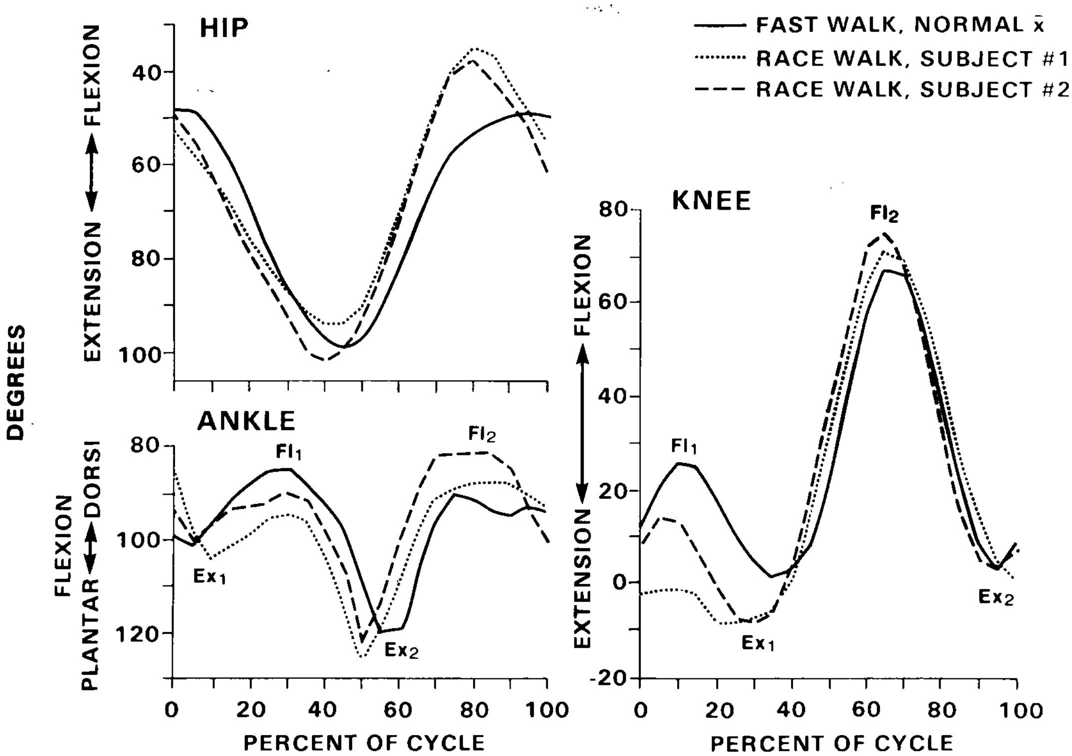

Figure 2. Mean patterns of flexion-extension of the hip, knee, and ankle of normal men during fast walking, and of each of the athletes during race walking. For the hip, the ordinate scale values represent the anterior angle between a lateral thigh target and a lateral pelvic target aligned from anterior superior to posterior superior iliac spine.

limb. Thus, the vertebral column of the race walker, as viewed posteriorly, alternately formed S-shaped and reverse S-shaped curves as weight supporting was shifted from one limb to the other.

Arm swing

During normal fast walking, the shoulder moved through an average range from 31° of hyperextension at ipsilateral heel strike to 8° flexion at contralateral heel strike. However, during race walking, peak shoulder hyperextension averaged 85° and peak shoulder flexion averaged 34° (Fig. 4).

During normal fast walking, elbow motion occurred through an average arc of motion from 15 to 55° flexion. In contrast, during race walking, the athletes were in marked flexion throughout the walking cycle. At the backward end of the swing, elbow flexion averaged 114° at the time of ipsilateral heel strike. The elbow extended to an average of only 92° of flexion when the arm was parallel to the trunk. The elbow then flexed sharply again as the shoulder flexed and rotated medially so that the hand reached its most medial and superior point at approximately the time of contralateral heel strike. The hand moved no farther medially than the midline of the body for both athletes and as far superiorly as the midsternum for Subject 1 and the level of the clavicle for Subject 2. In addition, the pectoral girdle was elevated excessively during double-limb support and depressed during single-limb support.

Displacement of the head and center of gravity of the body

During normal fast walking, the head moved laterally through a total excursion averaging 5.4 ± 3.4 cm; during race walking, the lateral motion of the head averaged 8 cm for Subject 1 and 12 cm for Subject 2.

The total excursion of the vertical pathway of the head was diminished to an average of 2 cm during race walking as compared to an average of 6.8 ± 1.1 cm during normal fast walking. Normally, the amplitude of the vertical pathway of the head is highest during single-limb-support periods and lowest during double-limb-support periods. In contrast, during race walking, the head was highest during double-limb support and lowest during single-limb support (Fig. 4).

During race walking the athletes decreased the vertical excursion of the center of gravity of the body below that of their free-speed walking. During free-speed walking, the excursion of the center of gravity was calculated to be 4.1 cm as compared to 2.8 cm during race walking (Fig. 4).

Electromyography

Figures 5 and 6 show tracings of the electromyographic signals monitored from 17 muscle groups during two representative cycles of fast walking and race walking for Subject 2. The patterns of muscle activity shown are similar to those recorded for Subject 1. All of the muscles showed an increase, and often a marked increase, in the amplitude of EMG

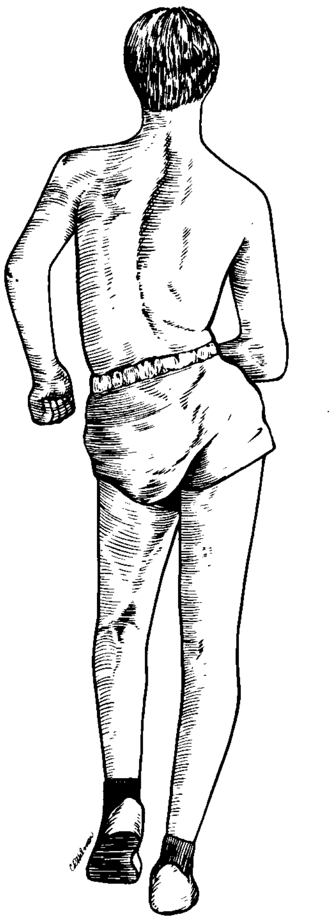

Figure 3. Tracing of Subject 1 during the right single-limb-support period of a race walking trial. The marked lateral tilt of the pelvis and the S-shaped curve of the vertebral column are evident.

activity during race walking. During race walking, most of the muscles also showed an increased duration of activity relative to the walking cycle time.

DISCUSSION

At first glance, race walker's movements look unnatural, exaggerated, and perhaps amusing. However, further study of the sport leads to a respect for the participants, the athletic skill required, and the purposefulness of the unique movement patterns. The sport provides vigorous exercise for not only lower limb muscles, but also muscles of the upper limbs and trunk.

We hypothesized that the rationale for the unnatural-appearing movements of race walking must lie in the need to diminish the amplitude of the vertical excursion of the mass center of the body in order to conserve mechanical energy. During walking, any large excursions or abrupt reversals in direction of motion of the mass center require excessive accelerative and decelerative forces. During race walking, the athlete executes specific automatic movement patterns which lower the center of gravity when it tends to be at a high point and raise it when it tends to be at a low point in order to minimize mechanical energy demands. Our calculations confirmed that the vertical excursion of the center of gravity had indeed been decreased during race walking to an even lesser excursion than during free-speed walking. The minimization of the excursion of the center of gravity was also reflected in the diminished vertical excursion of the head.

In normal walking, the yielding wave of knee flexion after the onset of weightbearing is one of the mechanisms which lowers the mass center at a time when it is rising to a high point. However, the race walking rules require the knee to be straight at some time during the stance phase.[3] This early

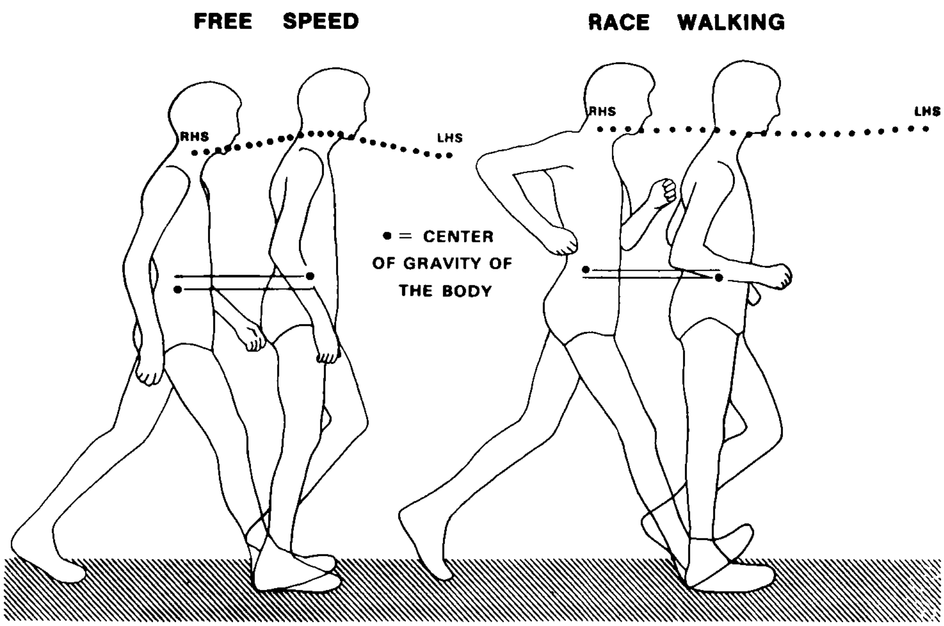

Figure 4. Tracings of Subject 1 at instants of double and single-limb support during free-speed and race walking illustrate arm swing and the vertical displacement of the neck and the center of gravity of the body.

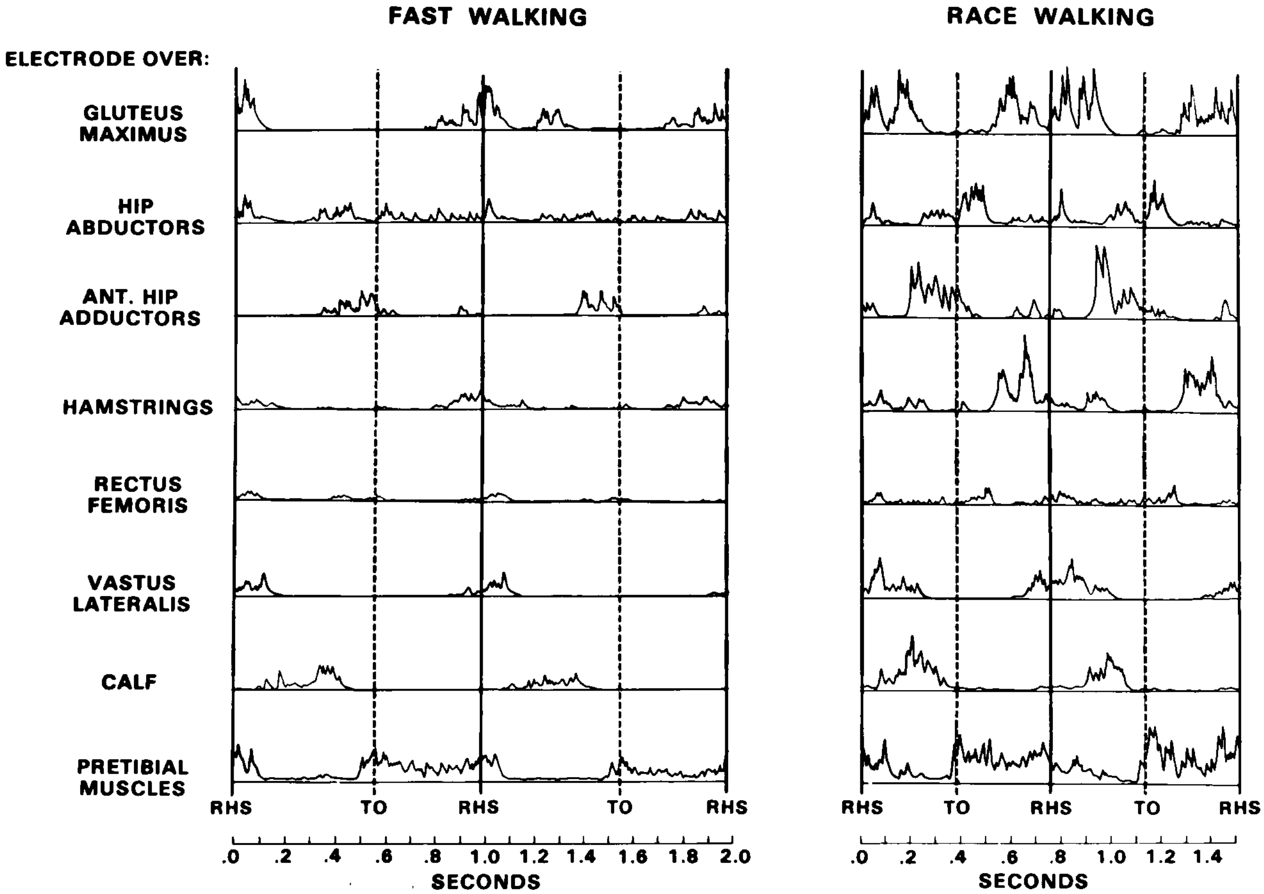

Figure 5. Tracings of full-wave rectified EMG signals from lower limb muscle groups of two consecutive cycles of fast and race walking for Subject 2. Vertical lines indicate right heel strike (RHS) and toe-off (TO).

stance knee extension would have the effect of abruptly and excessively raising the mass center at a time when it is already rising. However, the race walkers simultaneously execute motions which tend to lower the mass center of the body: they excessively adduct the supportive hip to allow excessive downward tilting of the pelvis on the swinging side and they depress the pectoral girdle, arm, and forearm segments (Fig. 4).

In order to raise the center of gravity of the body at the time that it is at its low point during double-limb support, the race walker elevates his pectoral girdle and upper limb and functionally lengthens the lower limbs at the instant of heel strike. The functional lengthening occurs by more plantarflexion of the ankle of the limb outstretched backward and by more extension of the knee and dorsiflexion of the ankle of the limb outstretched obliquely forward. The ankle dorsiflexion, together with the knee extension, contribute to functional lengthening by projecting the calcaneus forward.

When normal subjects progress from free-speed to fast walking, they lengthen their steps by increasing the flexion of the hip of the forward limb at the instant of heel strike.[7] We were surprised to find that the race walkers did not use this mechanism; their peak hip flexion was reached in midswing and this was followed by hip extension throughout the rest of swing similar to a hip pattern during running.[4] Perhaps this hip extension in late swing helped the walker gain momentum to pull the body forward, rather than restrain forward motion at, and shortly after, the instant of heel strike. The increase in step length achieved by the race walkers was also due to increased transverse rotation of the pelvis.

The relationship between the movement patterns and the patterns of muscle activity during race walking was also studied. The notably increased EMG activity during race walking, as compared to that during fast walking of the athletes, is no doubt related both to accelerating the limb and trunk movements and also to decelerating the exaggerated movements inherent to the walking patterns of race walkers.

The scapulo-humeral muscles active during fast walking were mainly associated with restraining the forward swing of the arm or initiating the backward swing (teres major, posterior deltoid). While all of the upper extremity muscles increased their activity during race walking, the most striking change was the pronounced activation of muscles initiating the forward thrust of the arm swing (pectoralis major, biceps brachii). In addition, the middle deltoid is probably necessary to circumduct the swinging arm past the trunk

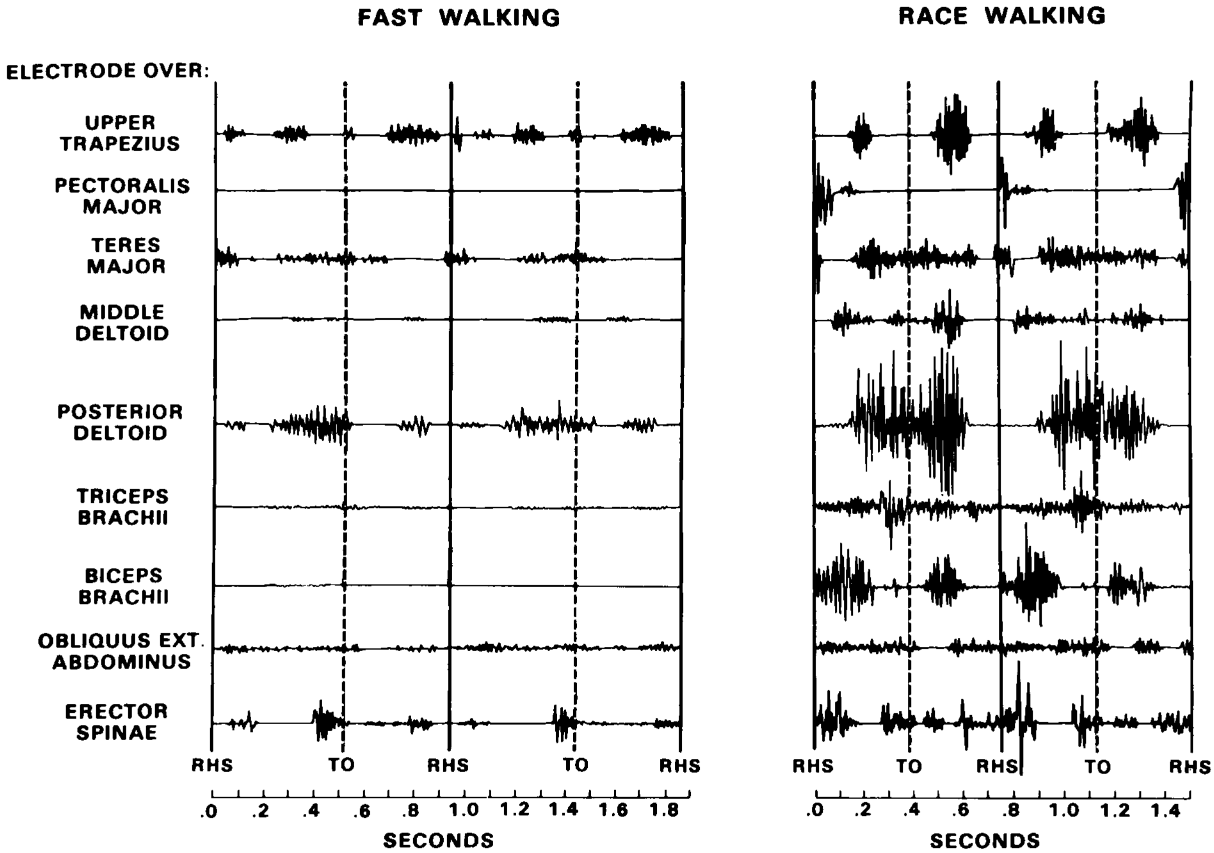

Figure 6. Tracings of raw EMG signals from the right upper limb and trunk muscles of two consecutive cycles of fast and race walking for Subject 2. Vertical lines indicate right heel strike (RHS) and toe-off (TO).

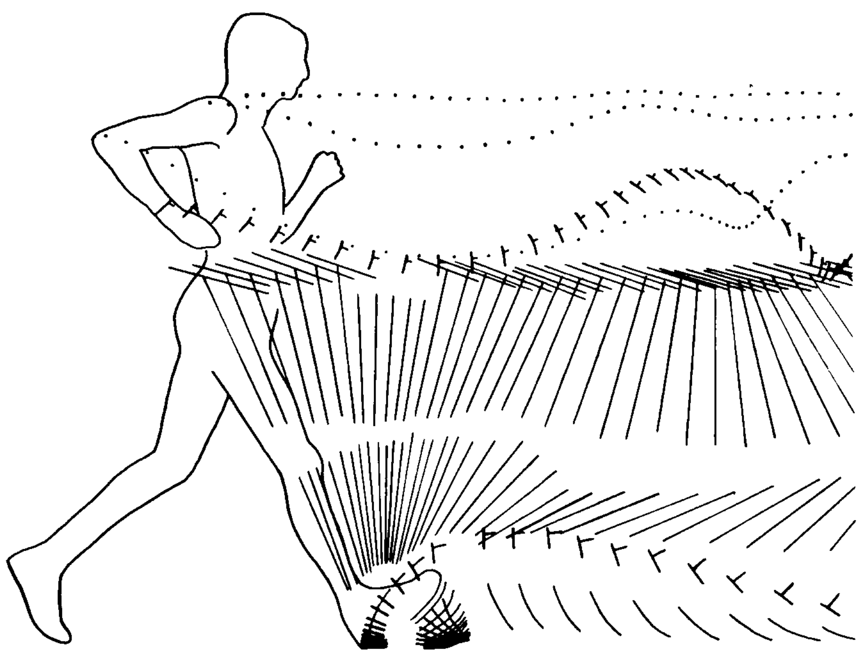

Figure 7. Tracings of the serial displacements of targets on the neck, shoulder, elbow, wrist, pelvis, thigh, leg, and shoe of Subject 1 during half of a race walking cycle. The recording speed was 128 frames/sec.

while the triceps is active in restraining elbow flexion and initiating elbow extension.

The increased activity of the erector spinae and lateral abdominal muscles is probably related to the reversals from the extremes of lateral trunk flexion associated with race walking (Fig. 3). The increased activity of the erector spinae at the heel-strike times also may be associated with producing or restraining the clockwise and counterclockwise rotations of the thorax and pelvis. In addition, the increased activity of the abdominal muscles may be limiting the amount of anterior-posterior pelvic tilting which is one of the few excursions which is not in excess of normal during race walking.

Lower limb muscle activity during race walking suggests that, after the onset of weightbearing, the gluteus maximus and hamstrings help the walker gain an erect torso over the forward-placed lower limb while the hip abductor muscles control the descent of the opposite-side pelvis (Fig. 5). The early stance phase activity of the vastus lateralis probably serves to rapidly lock the knee in hyperextension (Fig. 7) with the hamstrings acting simultaneously as dynamic ligaments to prevent stretching of the posterior capsule of the knee. The prolonged stance activity of the calf muscles restrains the forward rotation of the leg segment over the fixed foot (ankle dorsiflexion), and thus also indirectly helps to keep the knee extended by exerting a backward pull on the leg segment. The large burst of hip adductor muscle activity during the last half of the stance phase probably functions to decelerate or restrain hip extension.

In the early swing phase of race walking, the increase in the activity of the anterior hip abductor and adductor muscles and the rectus femoris probably functions to accelerate flexion of the hip of the swinging limb. In addition, this hip abductor muscle activity may also help abduct the swinging limb past the supportive limb. The small burst of hip adductor muscle activity at the end of the swing phase may serve to move the swinging limb into a more central position, ensuring a narrow stride width. The narrow stride width, in contrast to a wide stride width, undoubtedly helps to increase the step length. The large increase in activity of the gluteus maximus and hamstrings through the last half of the swing phase of race walking probably serves to decelerate hip flexion and then initiate the reversal into hip extension which begins at midswing for the athletes. No doubt, the late swing activity of the hamstrings also decelerates the knee extension of the swinging limb. The increase in the amplitude of swing-phase activity of the pretibial muscles most likely relates to the increased ankle dorsiflexion measured during race walking, as compared to normal fast walking.

One of the authors has treated several race walkers who were involved in vigorous training and who had complaints related to posterior knee pain, low back pain, or heel cord pain. Observations from this clinical experience, along with our quantitative data, have resulted in suggestions for preventing injuries which may be helpful to those involved in the management or training of race walkers. No doubt, the marked hyperextension of the knee during race walking (Fig. 7) puts stress on the posterior structures of the knee joint. Over a long period of time, this stress may be injurious to the ligaments. Thus, strengthening of the knee flexor muscles should be considered to provide dynamic ligamentous support against excessive hyperextension. The complaint of heel cord pain is generally relieved by prescribing a one-quarter-inch heel lift to be worn inside the shoe. The excessive transverse and frontal-plane rotation of the pelvis during race walking requires excessive lumbar spine motion. In view of the apparent need to execute these excessive motions while limiting anterior-posterior pelvic tilting during race walking, the physical conditioning program should also include stretching of the back muscles and vigorous strengthening exercises for the abdominal muscles. In our experience, these exercises have been beneficial in relieving these painful symptoms associated with race walking.

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