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A Lower-Extremities Kinematic Comparison of Deep-Water Running Styles and Treadmill Running

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[1]*Department of Health and Human Performance, Linfield College, McMinnville, Oregon 97128;* [2]*Department of Exercise and Sport Science, Oregon State University, Corvallis, Oregon 97331;* [3]*Division of Health and Physical Education, Western Oregon University, Monmouth, Oregon 97361.*

Abstract. Killgore, G.L., A.R. Wilcox, B.L. Caster, and T.M. Wood. A lower-extremities kinematic comparison of deep-water running styles and treadmill running. *J. Strength Cond. Res. 20(4):919–927. 2006.*—The purpose of this investigation was to identify a deep-water running (DWR) style that most closely approximates terrestrial running, particularly relative to the lower extremities. Twenty intercollegiate distance runners (women, $N = 12$; men, $N = 8$) were videotaped from the right sagittal view while running on a treadmill (TR) and in deep water at 55–60% of their TR $\dot{V}O_2$max using 2 DWR styles: cross-country (CC) and high-knee (HK). Variables of interest were horizontal (X) and vertical (Y) displacement of the knee and ankle, stride rate (SR), $\dot{V}O_2$, heart rate (HR), and rating of perceived exertion (RPE). Multivariate omnibus tests revealed statistically significant differences for RPE ($p < 0.001$). The post hoc pairwise comparisons revealed significant differences between TR and both DWR styles ($p < 0.001$). The kinematic variables multivariate omnibus tests were found to be statistically significant ($p < 0.001$ to $p < 0.019$). The post hoc pairwise comparisons revealed significant differences in SR ($p < 0.001$) between TR (1.25 ± 0.08 Hz) and both DWR styles and also between the CC (0.81 ± 0.08 Hz) and HK (1.14 ± 0.10 Hz) styles of DWR. The CC style of DWR was found to be similar to TR with respect to linear ankle displacement, whereas the HK style was significantly different from TR in all comparisons made for ankle and knee displacement. The CC style of DWR is recommended as an adjunct to distance running training if the goal is to mimic the specificity of the ankle linear horizontal displacement of land-based running, but the SR will be slower at a comparable percentage of $\dot{V}O_2$max.

Key Words. deep-water cross-country running, deep-water high knee running, XY displacement, stride rate, heart rate, Borg RPE scale, $\dot{V}O_2$

Introduction

Running has been described as "essentially a series of collisions with the ground" (20), and these collisions typically exhibit vertical ground reaction forces that are 2–4 times the runner's body weight (6). These impact forces, as well as training errors such as excessive mileage and increasing the total mileage too rapidly, are at least partially responsible for the creation of many running-related injuries (3, 6, 18).

A method of decreasing the running impact forces and the negative effects of excessive mileage is to supplement a runner's training program using deep-water running (DWR) (7, 11, 14, 15). Deep-water running, which is accomplished in water of sufficient depth to not allow the foot to touch the bottom (19), allows the runner to train using a similar movement pattern to that found on land without incurring the impact forces of land-based running, and thus reduces the repetitive loading of the musculoskeletal system (9, 18). Furthermore, DWR has been established as a mode of training to maintain cardiovascular fitness (15, 18). In fact, to date, most studies on DWR have focused on the physiological and metabolic responses to this mode of exercise (4, 5, 7, 10, 11, 14–16, 18, 22–24, 29). Based on these studies, it is commonly reported that treadmill running (TR) elicits higher maximal oxygen uptake and maximal heart rate (HR) as compared to DWR (5, 10, 14, 22–24, 29). However, Mercer and Jensen (22) provided evidence that during submaximal exercise, HR values exhibited no significant differences between running in each medium at comparable $\dot{V}O_2$.

Despite the use of DWR as a method of rehabilitation (9, 18, 25, 30) and, more recently, as supplementary training within a normal regimen, very little kinematic research focuses on the specific DWR technique. Several sources provide a qualitative assessment of proper DWR techniques. However, based on the stride rate (SR) data presented and the kinematic descriptions, it appears that the most commonly used DWR style is characterized by a high-knee (HK) or piston-like leg action (13, 21, 25, 30) that qualitatively is more similar to stair-stepping (21) than to running. In contrast, the cross-country (CC) style is, by design, qualitatively more like TR (21).

Few studies have specifically examined the biomechanics of DWR, and in those that have, their generalizability is limited by methodological factors such as a relatively small number of subjects (13, 25, 26), inadequate subject experience with DWR (13, 25), the DWR being conducted without subjects' using a buoyancy device (25), and the style of DWR not being specified (28). At present, no single study has adequately characterized the fundamental gait kinematics (i.e., horizontal and vertical positional data) of the HK and CC styles of DWR or compared them to TR. As a result, the baseline biomechanics of DWR gait patterns, particularly with respect to the technique or style, are not well understood, which limits our ability to make comparisons between DWR and TR. Therefore, the purpose of this study was to conduct a fundamental kinematics of the lower extremities and physiological analysis of 2 styles of DWR, CC and HK, and compare them to TR at equivalent $\dot{V}O_2$.

Methods

Experimental Approach to the Problem

It was determined that the best way to provide a baseline comparison of the 2 DWR styles (CC and HK) to land-

TABLE 1. Intraclass correlation coefficients for kinematic data.*

	TR	CC	HK
SR (Hz)	0.97	0.97	0.99
Knee Hor_{disp} (X_{min})	0.99	0.96	0.89
Knee Hor_{disp} (X_{max})	0.99	0.99	0.99
Knee $Vert_{disp}$ (Y_{min})	1.00	0.99	1.00
Knee $Vert_{disp}$ (Y_{max})	0.99	1.00	1.00
Ankle Hor_{disp} (X_{min})	0.96	0.99	0.99
Ankle Hor_{disp} (X_{max})	1.00	0.98	0.98
Ankle $Vert_{disp}$ (Y_{min})	0.97	0.99	0.99
Ankle $Vert_{disp}$ (Y_{max})	1.00	1.00	1.00

* TR = treadmill; CC = cross-country; HK = high knee; SR = stride rate.

based running (TR) was to analyze and plot the positional data of the minimum and maximum linear displacements of the knee and ankle relative to the hip as the zero point, while holding the subject to a fixed submaximal level of land-based $\dot{V}O_2$max. Typical temporal aspects of kinematic data (i.e., SR and horizontal and angular velocities and accelerations) are subject to a more viscous medium while in water (approximately 800 times) than on land (8), which makes direct comparisons of style of running in each media less straightforward; these were thus not used in lieu of the positional data. However, because cadence has been previously used to control workload (23), SR data were also analyzed. In addition, commonly reported joint angle minimums and maximums (13) yield less of a reflection of the actual pathway through which the distal end of a segment moves during the gait pattern, and thus provide less of an indicator of the overall range of motion. Our study design allowed a more direct comparison between gait patterns exhibited in differing media, both qualitatively and quantitatively. Likewise, Borg's 6–20 category scale and measurement of HR via an HR monitor provided direct comparisons between DWR and these commonly used standard tools of measurement for TR.

Subjects

Twenty experienced National Collegiate Athletic Association (NCAA) Division III distance runners participated in the study (Table 1). Subjects were recruited from the Linfield College, George Fox University, and Lewis and Clark College cross-country teams in the state of Oregon. All subjects read and signed an informed consent document, completed a health and training questionnaire, had skinfold measurements (1) recorded using a Lange skinfold caliper, and were instructed, according to American College of Sports Medicine guidelines, in the use of Borg's rating of perceived exertion (RPE) 6–20 category scale (1). The study was approved by the Institutional Review Boards for the Protection of Human Subjects of Oregon State University and Linfield College. In addition, each subject had recently completed a standardized health appraisal as per subjects' respective institutions' guidelines for intercollegiate sport participation (Northwest Conference and NCAA III).

Treadmill $\dot{V}O_2$max Test

Subjects performed a $\dot{V}O_2$max test on a Trackmaster TM215 Silver Series treadmill (JAS Manufacturing, Carrollton, TX). Subjects' $\dot{V}O_2$ was ascertained using a MedGraphics CPX Express System (MedGraphics, St. Paul, MN). Subjects began by warming up for approximately 5 minutes on the treadmill at an easy pace of 2.682 $m\cdot s^{-1}$ for men and 2.235 $m\cdot s^{-1}$ for women. The treadmill protocol consisted of starting at 3.129 $m\cdot s^{-1}$ for men and 2.682 $m\cdot s^{-1}$ for women, at 0° elevation, and progressing by 0.224 $m\cdot s^{-1}\cdot min^{-1}$ until 4.917 $m\cdot s^{-1}$ for men and 4.47 $m\cdot s^{-1}$ for women was achieved. At this point, the speed was held constant and treadmill elevation increased by 1%$\cdot min^{-1}$ until volitional fatigue. Heart rate (HR monitor; Polar, Lake Success, NY) and RPE (Borg Category 6–20 scale) were manually recorded every 30 seconds. To aid the subject in determination of RPE, a chart of Borg's scale was placed on the wall at eye level at a distance of 3.50 m from the treadmill. The highest average recorded $\dot{V}O_2$ value over a 1-minute interval was accepted as $\dot{V}O_2$max when the subject met 3 out of 4 of the following criteria: failed to demonstrate an increase in HR, reached a plateau in oxygen uptake with further increases in exercise intensity, reached a respiratory exchange ratio of $>$1.15, and reached a RPE of $>$17 on Borg's 6–20 scale (1). Based on these criteria, all subjects successfully attained $\dot{V}O_2$max.

Treadmill Submaximal $\dot{V}O_2$ Test

To establish the physiological and biomechanical responses to TR at 60% of $\dot{V}O_2$max, a separate treadmill session was conducted. The treadmill was set at an appropriate speed (2.235–3.353 $m\cdot s^{-1}$) at 0° elevation to allow the subject to run for 5–6 minutes at 60% of $\dot{V}O_2$max based upon the results from the measured $\dot{V}O_2$ during the $\dot{V}O_2$max test. The physiological and kinematic test data from this test were subsequently used as the comparator values in the DWR trials.

Treadmill Biomechanical Data

To collect the kinematic data, the subjects were attired in comfortable running shorts, with women wearing a jog bra or other suitable garment, and men shirtless. This allowed for proper placement of the biomechanical joint markers (3M highly-reflective adhesive tape [3M, St. Paul, MN], approximately 2.5 cm in diameter) on the right side of each subject at the center points of the shoulder joint, elbow joint, wrist joint, hip joint at the head of the femur, knee joint, lateral malleolus, lateral calcaneus, and fifth metatarsal head. A Panasonic AG-456 S-VHS movie camera (Panasonic, Secaucus, NJ) was used for the collection of kinematic data while subjects ran on the treadmill. The camera specifications include more than 400 lines of resolution, 3-lux light sensitivity, and a F1.6 lens. Each subject was videotaped throughout the complete trial at 30 frames per second (fps) from the right sagittal view with Sony VHS videotape (Sony, Tokyo, Japan). A scale factor of 1 m was determined via 2 highly reflective tape markers placed on the bottom of the treadmill perpendicular to the camera. These data were hand-digitized on a Peak Motus 2000 2-D system (Peak Performance Technologies, Englewood, CO) using a Panasonic AG-1980P 4-head video cassette recorder.

Deep-Water Running Orientation

Each subject completed a questionnaire regarding DWR experience, general water immersion comfort levels, weekly running mileage, and injury history. Subjects then viewed and discussed with the investigator a brief videotape of the DWR styles HK and CC. A brief description of each style follows and closely resembles those previously outlined by other investigators (18, 21, 24, 30). In general, in both styles (HK and CC), the water is at shoulder level with the head held in a neutral position facing forward. The body leans slightly forward of a vertical position. The arm carriage should be identical to land-based running, with motion primarily from the shoulder joint. The hands are held in a slightly-clenched-fist position to decrease the likelihood of using a dog-paddling–type motion. Hip flexion reaches a position of approximately 60–80°, followed by full extension of the leg. The foot moves from approximately 0° dorsiflexion at full hip flexion to approximately 50–70° of plantarflexion when the leg is fully extended. The major differences between the HK and CC styles of DWR are that the HK style leg action (21) is primarily in a vertical plane with the legs moving straight up and down in a pistonlike movement pattern or a cyclic action that is somewhat reminiscent of stair-stepping, marching in place, or bicycling with very little horizontal displacement present, whereas the CC style, particularly relative to horizontal range of motion, looks qualitatively more like that of a runner (21) moving at a faster velocity, e.g., a 5-km race pace in land-based running, primarily because of the increased horizontal displacement of the ankle. Because prior experience in DWR has been implicated as a factor in metabolic responses to DWR (11), 3 subsequent 30-minute technique practice sessions in a swimming pool were provided. During practice sessions, each subject received underwater video visual feedback via a video monitor connected to the underwater camera (AquaCam, Portsmouth, NH) and verbal feedback from the investigator.

Deep-Water Running

The DWR tests took place in the deep end of a swimming pool (25 × 20 m) with a depth of 3.96 m, so that the subjects' feet never touched the bottom of the pool (19), and at an average temperature of 27.2°C (± 0.7°). The DWR session included 2 trials (HK and CC), each 5–6 minutes in length, with a rest period of at least 2–3 minutes between trials. Each trial was conducted at a target intensity that was 60% of the subject's maximal treadmill $\dot{V}O_2$, and steady-state physiological data were collected over the final 3 minutes of each trial. To insure subject compliance, an investigator provided verbal feedback regarding $\dot{V}O_2$ and technique from the metabolic cart monitor and the video camera monitor, respectively. The subject's $\dot{V}O_2$, HR, and RPE were continuously monitored throughout all trials, with HR and RPE values recorded every 30 seconds. To aid the subject in determination of RPE, a chart of Borg's scale was hung over the water from a rope at eye level at a distance of 3.80 m from the subject. The order of tests was counterbalanced according to the method described by Girden (12). All male subjects were shirtless and attired in either running shorts or a swim suit. Female subjects wore either running shorts and a jog bra or a swim suit. This allowed for proper placement of the Polar M52 HR monitor as well as the joint markers. Each joint marker consisted of a circle approximately 2.5 cm in diameter; joint markers were drawn with a black indelible marker at the joint centers previously described for the treadmill test (a pilot investigation revealed that the black joint center provided the best clarity for underwater filming).The subject then proceeded to put the AquaJogger Pro (Excel Sports Sciences, Eugene, OR) flotation device around his or her waist and entered the pool, where the next 5–10 minutes were spent warming up using a running motion at a self-determined level of moderate exertion. The subject was then tethered to the side of the pool, at a distance that allowed for a full range of motion in the subject's stride patterns, using a commercial tether (Excel Sports Sciences). A surface flotation wave-limiting device was affixed to the diving blocks on the pool deck. This device was designed to allow the head of each subject to remain in a comfortably vertical position and greatly reduced the likelihood of getting the pneumotach or sampling line wet. All trials were recorded underwater via a color AquaCam underwater video camera that was positioned at the side of the pool perpendicular to the subject at a depth of 0.93 m and at a distance of 6.74 m from the subject. The camera specifications include 480 lines of resolution, Sony HyperHAD pickup device, autoelectric iris with image enhance processor chip, 2-lux light sensitivity, and 4.3-mm lens. Data were stored via a cable into the video input of a Panansonic AG 1980P VCR at 30 fps. Figure 1 graphically illustrates the arrangement of the data collection instrumentation. A scale factor was established via a pole marked at a length of 1 m held in place underwater at the same distance as the subject and perpendicular to the camera. Data from 10 consecutive representative strides during the last 3 minutes of each trial were then digitized on a Peak Motus 2-D system, as previously described.

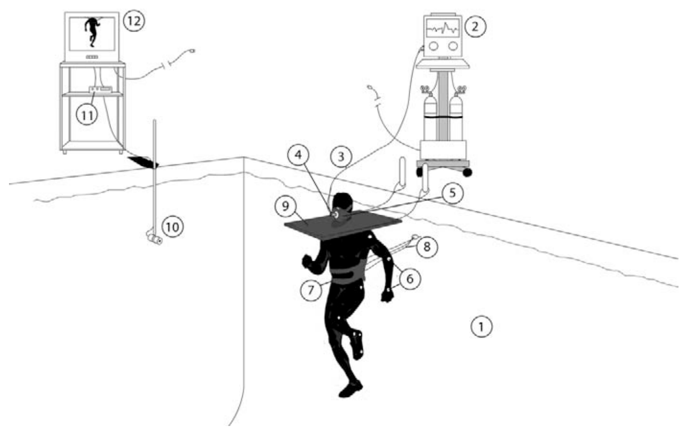

FIGURE 1. Data collection setup. 1 = pool, deep end (3.96 m) average temperature 27.2°C; 2 = metabolic cart monitor; 3 = sampling line; 4 = pneumotach; 5 = neoprene aviator mask; 6 = joint centers; 7 = AquaJogger Pro flotation device; 8 = commercial tether, which holds subject in vicinity of wall; 9 = surface flotation wave-limiting device, which allows head of subject to remain comfortable and vertical; 10 = AquaCam; underwater video camera (depth, 0.93 m; distance from subject, 6.74 m); 11 = Panasonic AG 1980P VCR; 12 = video camera monitor, which provides underwater view.

Statistical Analyses

For each variable, repeated measures analysis of variance (ANOVA) with a multivariate omnibus test of significance was used to determine mean differences across trials. Each variable found to be statistically significant in the multivariate tests was further subjected to a pairwise post hoc analysis using paired t-tests. To limit the likeli-

TABLE 2. Subject characteristics.*

Variable	Women (N = 12)	Men (N = 8)
Age (y)	19.8 ± 0.9	19.6 ± 1.1
Height (cm)	166.1 ± 0.9	182.1 ± 7.9
Weight (kg)	57.1 ± 6.9	71.3 ± 5.1
Body fat (%)	16.8 ± 3.9	6.9 ± 1.9
$\dot{V}O_2max$ (ml·kg^{-1}·min^{-1})	49.1 ± 3.4	56.6 ± 2.9
Minimum km·wk^{-1}	56.4 ± 13.7	72.4 ± 16.7
Maximum km·wk^{-1}	70.0 ± 16.1	91.7 ± 20.9
Best 5-km time (min:s)	19:48 ± 58.7s	16:36 ± 40.7s

* Values are mean ± *SD*.

hood of committing a type I error to 0.05, a Bonferroni adjustment was performed; with 3 pairwise post hoc comparisons, the adjusted alpha for each pairwise comparison was 0.017. To determine confidence in the consistency of mean data for 10 representative strides, intraclass correlation coefficients were calculated on each individual stride within the 10-stride mean data and are presented in Table 1. Using a formula for estimating power in repeated measures designs (27), it was determined a priori that using 20 subjects with an alpha significance level of 0.05 resulted in estimated statistical power of 0.693–0.980 for the physiological variables and 0.955–1.000 for the biomechanical variables. The statistical software utilized for all analyses was SPSS (version 11.5; SPSS, Inc., Chicago, IL).

RESULTS

Physiological Data

Subject characteristics are summarized in Table 2. The subjects in this study can be considered average NCAA Division III cross-country runners based on both their physiological data and their best 5-km race performances. Many of the subjects, particularly the male subjects, were primarily middle-distance runners in track and field. Only 1 subject had no prior experience with an AquaJogger, with 93% having previously used an AquaJogger more than 6–10 times. The study commenced at the beginning of the competitive collegiate cross-country season and concluded prior to the end of the season. Table 3 provides a summary of the physiological/perceptual steady-state data averaged over all subjects, under each experimental condition, and by gender. The multivariate omnibus test for the combined $\dot{V}O_2$ was statistically significant ($p < 0.023$). However, the post hoc pairwise (Table 4) comparisons did not yield statistically significant differences in $\dot{V}O_2$ between TR and DWR. Furthermore, the $\dot{V}O_2$ effect sizes found in Table 4 demonstrate relatively small differences and the by-gender multivariate test yielded nonsignificance. The percent of $\dot{V}O_2$ data (Table 3) showed that the trials fell within a narrow range of values (58.0–60.2% ± 2.9–4.2%). With no statistically significant pairwise comparison of differences and the small effect sizes, the investigators conclude that the design objective to equalize $\dot{V}O_2$ across trials was satisfied. The multivariate omnibus test for HR was not found to be statistically significant; thus, no post hoc analysis was conducted. There were a statistically significant ($p < 0.001$) main effect and large effect sizes for the RPE responses (Table 4). The post hoc analysis revealed statistically significant differences between RPE responses for

TABLE 3. Physiological/perceptual data summary.*

	TR	CC	HK
$\dot{V}O_2$			
Combined	31.1 ± 3.4	31.1 ± 3.5	30.2 ± 3.4
Women	29.4 ± 2.4	28.8 ± 2.2	28.3 ± 2.0
Men	33.7 ± 2.4	34.1 ± 2.2	33.0 ± 1.7
$\dot{V}O_2$%			
Combined	59.5 ± 1.8	59.5 ± 3.6	57.9 ± 2.2
Women	59.5 ± 2.0	58.8 ± 3.7	57.7 ± 2.5
Men	59.6 ± 1.6	60.4 ± 3.2	58.3 ± 1.8
HR			
Combined	137.9 ± 9.4	135.1 ± 11.2	132.6 ± 9.6
Women	138.8 ± 10.0	135.4 ± 10.0	132.0 ± 9.1
Men	134.8 ± 7.0	133.6 ± 9.7	133.1 ± 8.3
RPE			
Combined	11.8 ± 1.2	13.5 ± 1.2	13.4 ± 0.8
Women	11.7 ± 0.7	13.2 ± 0.9	13.1 ± 0.8
Men	11.3 ± 1.6	13.3 ± 1.2	13.3 ± 0.7

* Values are mean ± *SD*; TR = treadmill; CC = cross-country; HK = high knee; HR = heart rate; RPE = rating of perceived exertion.

TABLE 4. Statistical pairwise comparisons and effect sizes for physiological/perceptual data (combined).*

	TR/CC	TR/HK	CC/HK
Combined			
HR	NS	NS	NS
	(0.27)	(0.62)	(0.24)
$\dot{V}O_2$	0.687	0.035	0.022
	(−0.07)	(0.28)	(0.36)
RPE	0.000†	0.000†	0.442
	(−1.48)	(−1.52)	(0.17)
Women			
HR	0.346	0.037	0.031
	(0.26)	(0.25)	(0.02)
$\dot{V}O_2$	NS	NS	NS
	(0.008)	(0.51)	(0.57)
RPE	0.000†	0.001†	0.346
	(1.53)	(1.58)	(0.53)
Men			
HR	NS	NS	NS
	(0.26)	(0.25)	(0.02)
$\dot{V}O_2$	NS	NS	NS
	(0.25)	(0.21)	(0.53)
RPE	NS	NS	NS
	(1.45)	(1.59)	(0.12)

* Numbers in parentheses indicate effect size. NS = nonsignificance on multivariate test; a = <0.017 (based on Bonferroni post hoc analysis); TR = treadmill; CC = cross-country; HK = high knee; HR = heart rate; RPE = rating of perceived exertion.
† <0.017 (based on Bonferroni post hoc analysis).

TR compared to each style of DWR ($p < 0.001$). The pairwise RPE responses between the DWR styles were not found to be statistically significant. Values for RPE during DWR were found to be 1.6–1.7 higher than those found during TR. The by-gender effect sizes were also large between TR and DWR.

Biomechanical Variables

Figures 2 and 3 graphically illustrate the knee and ankle X and Y displacements of a single stride for a representative female and male subject in each style respectively. Data were filtered (Butterworth for TR knee and ankle:

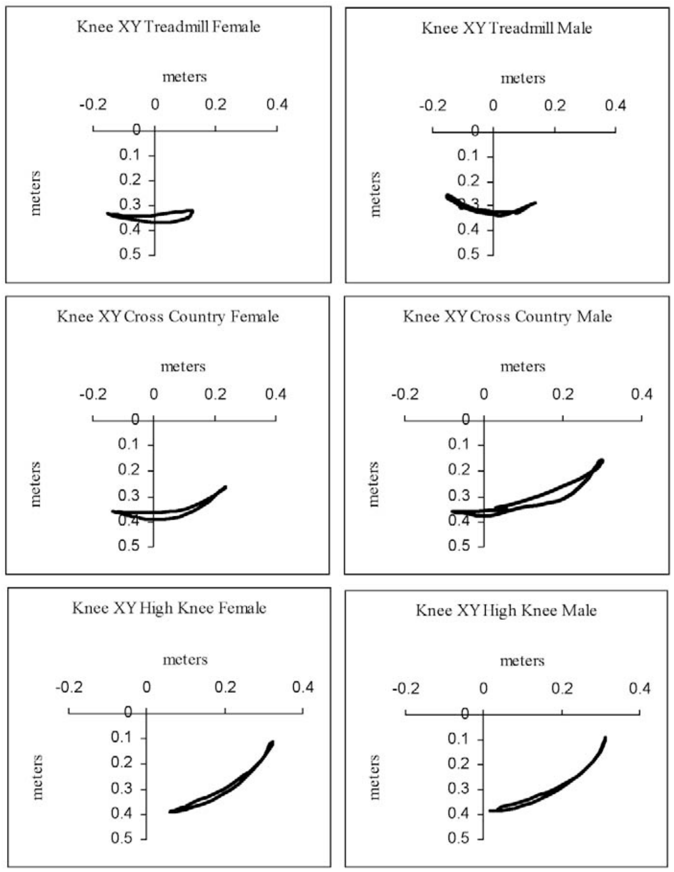

FIGURE 2. Knee displacement relative to the hip as the zero point (transformed XY) of 1 representative stride for a female and a male subject. Values are in meters, with negative numbers indicating a position posterior to the hip.

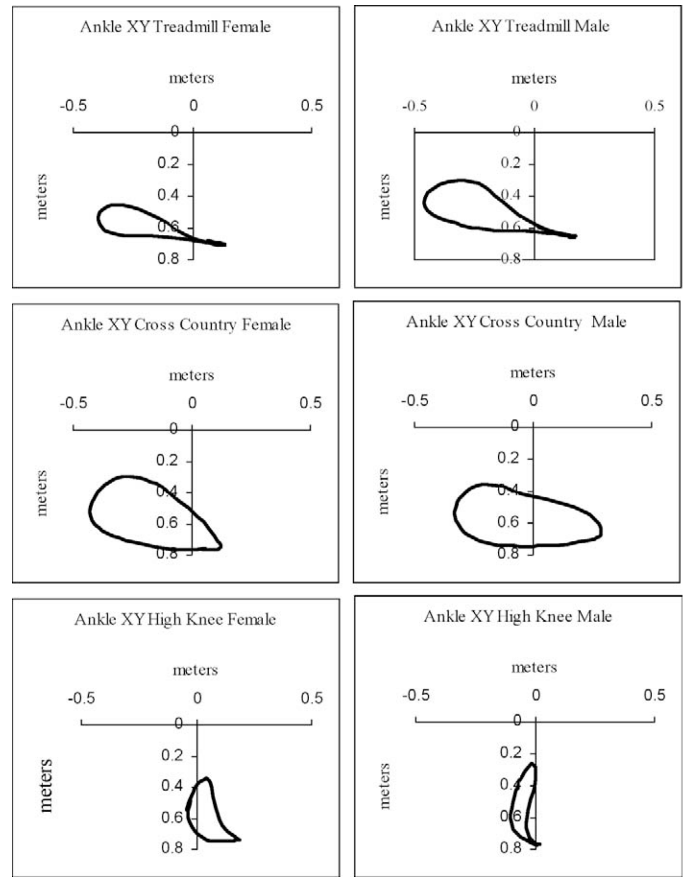

FIGURE 3. Ankle displacement relative to the hip as the zero point (transformed XY) of 1 representative stride for a female and a male subject. Values are in meters, with negative numbers indicating a position posterior to the hip.

4.4–5.4 Fz; DWR knee and ankle: 3.8–4.6 Fz) and are presented relative to the hip as the zero point, where the positive numbers indicate the knee and ankle anterior to the hip and the negative numbers are posterior to the hip.

Figure 2 and particularly Figure 3 illustrate qualitative similarities between the horizontal displacements of the ankle during TR and the CC style of DWR. Conversely, the relative lack of horizontal displacement of the ankle and the more pronounced vertical displacements in the HK style of DWR are evident in these figures.

Tables 5 and 6 provide means and standard deviations for the kinematic variables of the lower extremities over 10 consecutive representative strides. All pairwise comparisons are presented in Tables 7–9. Stride rate in this study was defined as 1 complete stride cycle from maximum knee flexion to maximum knee flexion of the right leg. The SR results demonstrated a statistically significant difference between all styles of running ($p < 0.001$). A comparison of SRs between the CC style of DWR and TR demonstrates that land-based running is accomplished at a much faster SR (1.25 ± 0.08 Hz) than is CC (0.81 ± 0.08 Hz). The very large effect sizes corroborate this observation (CC: 5.50). The HK style exhibits an SR (HK: 1.14 ± 0.10 Hz) that is intermediate to TR and the CC style: HK SR was significantly faster than the CC style, but was also significantly slower than TR SRs and with large effect sizes (1.22 HK).

All XY displacement data were found to be statistically significant ($p < 0.001$ to $p < 0.019$). Closer examination of the XY pairwise comparisons for all subjects (Table 7), however, reveals quantitative similarities between the CC style and the TR data relative to the ankle horizontal minimum and maximum displacement (AXMN, AXMX), ankle vertical minimum displacement (AYMN), knee horizontal minimum displacement (KXMX), and knee vertical minimum displacement (KYMN). Conversely, all kinematic variables (knee horizontal minimum displacement [KXMN], KXMX, KYMN, KYMX, AXMN, AXMX, AYMN, and ankle vertical maximum displacement [AYMX]) demonstrated a statistically significant difference between TR and the HK style of DWR. The pairwise comparisons between the 2 DWR styles (CC and HK) yielded statistically significant differences in KXMN, KXMX, KYMN, AXMN, AXMX. The only by-gender nonsignificant difference was found for males (AYMN).

DISCUSSION

The primary aim of this study was to characterize 2 styles of DWR as compared to terrestrial running with respect to the specific fundamental kinematics of the movements of the lower extremities. The key findings of the present investigation were that significant lower-extremity kinematic differences exist between the 2 DWR styles, CC and HK, and that as compared to TR, the CC style is more like land-based running at equivalent $\dot{V}O_2$ relative to the overall range of motion of the gait pattern. In contrast, although significantly different, the HK style is more like

TABLE 5. Kinematics summary of stride rate (SR) and knee positional data.*

	TR	CC	HK
SR (Hz)			
Combined	1.34 ± 0.08	0.90 ± 0.08	1.15 ± 0.11
Women	1.35 ± 0.07	0.91 ± 0.06	1.17 ± 0.08
Men	1.33 ± 0.08	0.88 ± 0.10	1.12 ± 0.15
KneeHor (X_{min} m)†			
Combined	0.169 ± 0.03	0.308 ± 0.08	0.357 ± 0.05
Women	0.160 ± 0.03	0.279 ± 0.07	0.347 ± 0.04
Men	0.181 ± 0.03	0.351 ± 0.07	0.373 ± 0.07
KneeHor (X_{max} m)†			
Combined	−0.156 ± 0.03	−0.135 ± 0.06	0.001 ± 0.08
Women	−0.152 ± 0.03	−0.151 ± 0.06	0.000 ± 0.08
Men	−0.162 ± 0.02	−0.109 ± 0.06	0.002 ± 0.08
KneeVert (Y_{min} m)†			
Combined	0.304 ± 0.04	0.271 ± 0.08	0.154 ± 0.11
Women	0.297 ± 0.04	0.279 ± 0.09	0.155 ± 0.09
Men	0.314 ± 0.03	0.259 ± 0.06	0.154 ± 0.14
KneeVert (Y_{max} m)†			
Combined	0.373 ± 0.03	0.470 ± 0.05	0.461 ± 0.05
Women	0.363 ± 0.03	0.450 ± 0.04	0.444 ± 0.04
Men	0.387 ± 0.03	0.500 ± 0.06	0.488 ± 0.06

* Values are mean ± *SD*; TR = treadmill; CC = cross-country; HK = high knee; SR = stride rate; KneeHor (X_{min} m) = knee horizontal minimum displacement value in meters; KneeHor (X_{max} m) = knee horizontal maximum displacement value in meters; KneeVert (Y_{min} m) = knee vertical minimum displacement value in meters; KneeVert (Y_{max} m) = knee vertical maximum displacement value in meters.

† All minimum and maximum positional values are relative to the difference between the hip as a reference point and the joint center of interest (knee) and are reported in meters.

TABLE 6. Kinematics summary of ankle positional data.*

	TR	CC	HK
AnkleHor (X_{min} m)†			
Combined	−0.186 ± 0.03	−0.165 ± 0.16	0.186 ± 0.11
Women	−0.179 ± 0.04	−0.107 ± 0.12	−0.040 ± 0.17
Men	−0.197 ± 0.03	−0.252 ± 0.19	−0.134 ± 0.19
AnkleHor (X_{max} m)†			
Combined	0.447 ± 0.05	0.454 ± 0.08	0.186 ± 0.11
Women	0.425 ± 0.04	0.459 ± 0.08	0.175 ± 0.13
Men	0.480 ± 0.04	0.446 ± 0.10	0.203 ± 0.06
AnkleVert (X_{min} m)†			
Combined	0.414 ± 0.11	0.397 ± 0.11	0.338 ± 0.07
Women	0.415 ± 0.07	0.356 ± 0.07	0.332 ± 0.05
Men	0.423 ± 0.15	0.436 ± 0.15	0.343 ± 0.09
AnkleVert (X_{max} m)†			
Combined	0.707 ± 0.09	0.931 ± 0.11	0.916 ± 0.11
Women	0.711 ± 0.04	0.902 ± 0.09	0.893 ± 0.10
Men	0.714 ± 0.15	0.995 ± 0.12	0.973 ± 0.11

* Values are mean ± *SD*; AnkleHor (X_{min} m) = ankle horizontal minimum displacement value in meters; AnkleHor (X_{max} m) = ankle horizontal maximum displacement value in meters; AnkleVert (X_{min} m) = ankle vertical minimum displacement value in meters; AnkleVert (X_{max} m) = ankle vertical maximum displacement value in meters.

† All minimum and maximum positional values are relative to the difference between the hip as a reference point and the joint center of interest (ankle) and are reported in meters.

TABLE 7. Statistical pairwise comparisons and effect sizes for kinematic data (all subjects).*

	TR/CC	TR/HK	CC/HK
SR	0.000†	0.000†	0.000†
	(−5.5)	(−1.22)	(−3.67)
KXMN	0.000†	0.000†	0.001†
	(−2.32)	(−2.83)	(−0.41)
KXMX	0.178	0.000†	0.000†
	(−0.35)	(−2.62)	(−1.70)
KYMN	0.044	0.000†	0.000†
	(−0.55)	(−1.88)	(−1.17)
KYMX	0.000†	0.000†	0.029
	(−2.43)	(−2.20)	(−0.18)
AXMN	0.532	0.010†	0.004†
	(−0.18)	(−1.36)	(−0.80)
AXMX	0.761	0.000†	0.000†
	(−0.10)	(−2.9)	(−2.68)
AYMN	0.532	0.010†	0.021
	(−0.16)	(−0.84)	(−0.66)
AYMX	0.000†	0.000†	0.029
	(−2.24)	(−2.09)	(−0.14)

* Numbers in parentheses indicate effect size. TR = treadmill; CC = cross-country; HK = high knee; SR = stride rate; KXMN = knee horizontal minimum displacement; KXMX = knee horizontal maximum displacement; KYMN = knee vertical minimum displacement; KYMX = knee vertical maximum displacement; AXMN = ankle horizontal minimum displacement; AXMX = ankle horizontal maximum displacement; AYMN = ankle vertical minimum displacement; AYMX = ankle vertical maximum displacement.

† <0.017 (based on Bonferroni post hoc analysis).

TABLE 8. Statistical pairwise comparisons and effect sizes for kinematic data (female subjects only).*

	TR/CC	TR/HK	CC/HK
SR	0.000†	0.000†	0.000†
	(6.43)	(2.71)	(3.71)
KXMN	0.000†	0.000†	0.001†
	(1.98)	(4.68)	(1.13)
KXMX	0.963	0.000†	0.000†
	(0.02)	(2.50)	(2.13)
KYMN	0.312	0.000†	0.001†
	(0.37)	(2.03)	(1.29)
KYMX	0.000†	0.000†	0.211
	(2.18)	(2.03)	(0.15)
AXMN	0.046	0.005†	0.18
	(−.08)	(−1.63)	(−1.05)
AXMX	0.168	0.000†	0.000†
	(−0.57)	(2.5)	(2.58)
AYMN	0.198	0.008†	0.152
	(0.53)	(1.04)	(0.51)
AYMX	0.000†	0.000†	0.276
	(2.64)	(2.49)	(0.12)

* Numbers in parentheses indicate effect size. TR = treadmill; CC = cross-country; HK = high knee; SR = stride rate; KXMN = knee horizontal minimum displacement; KXMX = knee horizontal maximum displacement; KYMN = knee vertical minimum displacement; KYMX = knee vertical maximum displacement; AXMN = ankle horizontal minimum displacement; AXMX = ankle horizontal maximum displacement; AYMN = ankle vertical minimum displacement; AYMX = ankle vertical maximum displacement.

† <0.017 (based on Bonferroni post hoc analysis).

TABLE 9. Statistical pairwise comparisons and effect sizes for kinematic data (male subjects only).*

	TR/CC	TR/HK	CC/HK
SR	0.000†	0.007†	0.004†
	(4.97)	(1.66)	(1.90)
KXMN	0.000†	0.000†	0.001†
	(1.98)	(4.68)	(1.13)
KXMX	0.178	0.000†	0.000†
	(0.02)	(2.50)	(2.13)
KYMN	0.044	0.000†	0.000†
	(0.37)	(2.03)	(1.29)
KYMX	0.000†	0.000†	0.029
	(2.18)	(2.03)	(0.15)
AXMN	0.563	0.000†	0.004†
	(0.43)	(0.18)	(−0.04)
AXMX	0.761	0.000†	0.000†
	(0.43)	(5.55)	(3.04)
AYMN	NS	NS	NS
	(0.08)	(0.67)	(0.77)
AYMX	0.000†	0.000†	0.029
	(2.16)	(1.99)	(0.19)

* Numbers in parentheses indicate effect size. TR = treadmill; CC = cross-country; HK = high knee; SR = stride rate; KXMN = knee horizontal minimum displacement; KXMX = knee horizontal maximum displacement; KYMN = knee vertical minimum displacement; KYMX = knee vertical maximum displacement; AXMN = ankle horizontal minimum displacement; AXMX = ankle horizontal maximum displacement; AYMN = ankle vertical minimum displacement; AYMX = ankle vertical maximum displacement.

† <0.017 (based on Bonferroni post hoc analysis).

TR with regard to SR. Heart rates were not found to be significantly different between running styles.

An investigation of DWR as compared to land-based running is complicated by the differences between the media in which the subjects moved. One of the primary forces a runner encounters on land is gravity, whereas DWR is largely weight-supported. Consequently, the normal ground reaction forces do not exist in the water. Likewise, the ability of a normal runner to maintain an efficient stride pattern while running on land is compromised in the water by the increased density of water (approximately 800 times that of air), which is a much more viscous medium in which the runner must move (8). The viscosity of water offers an accommodating resistance (isokinetic) primarily because of drag, which increases resistance as the intensity of the movement in the water increases (7, 17). Drag can be increased in water by increasing the velocity of the movement or the surface area that is exposed to the reaction force of the water that is being pushed against. An equally important factor is the effect of buoyancy on the ability of a runner to maintain proper posture, including a neutral head position, and appropriate overall running mechanics. Buoyancy can act to assist or resist movements while in the water (17). Our pilot investigation revealed that the deep-water runner, especially the runner who is quite lean, should wear a properly fitted buoyancy device, which assists the runner in the maintenance of appropriate running mechanics. In addition, to maximize effectiveness, the device appears to provide optimal buoyancy when worn near the center of mass of the runner. When the buoyancy device is worn as described, an increase in the vertical resistance buoyancy force will act to drive the runner toward the surface, thus allowing the runner to experience an increased ease in breathing by maintaining the head in a more neutral position. Furthermore, our pilot investigation revealed that when a deep-water runner, especially a runner who is quite lean, does not wear any type of buoyancy device, as was the case in one investigation of the biomechanics of water running (25), the kinematics of the running gait will be severely limited to a style that is very similar to treading water or stair-stepping. Appreciating these differences between media perhaps allows for a more complete understanding of some of the manifestations found in the current investigation.

This study was designed to conduct all trials at the same absolute $\dot{V}O_2$. The main effect for $\dot{V}O_2$ (combined) was statistically significant. However, the effect size was relatively small and no pairwise comparison revealed statistical significance. Based on the small effect sizes and the narrow range among the $\%\dot{V}O_2max$ values (58.0–60.2%) between trials, we are satisfied that the subjects were performing at equivalent $\dot{V}O_2$ in all trials.

The results indicated that at similar levels of $\dot{V}O_2$, the HR values were not statistically different. These findings are consistent with other submaximal studies with experienced runners (7, 22). In contrast, studies have reported maximal HR during TR to be approximately 15 (± 5.5) b·min^{-1} higher than the maximal HR values found in DWR (5, 10, 14, 22, 29), which suggests that the DWR trials in this study may have been conducted at a higher percentage of the subjects' maximal HR. Treadmill $\dot{V}O_2max$ has also been reported to be approximately 15.6% (±6.5%) higher than DWR $\dot{V}O_2max$ (5, 10, 14, 22, 29). Even though the absolute $\dot{V}O_2$ was controlled across all trials, the perception of the work intensity (RPE) was significantly higher during the DWR trials than during TR. The RPE values were 1.6–1.7 points higher on the 20-point Borg scale during DWR than during TR. The DWR RPE values (13.4–13.5) compare well with those provided by Baretta (2) for a moderate intensity of 50–74% of $\dot{V}O_2max$ in DWR. Other studies (4, 14, 24, 29) also provided evidence that the RPE values are significantly higher in DWR as compared to TR at submaximal intensities. The higher RPE responses reported supports the view that the subjects were working at a higher relative percentage of $\dot{V}O_2max$ during DWR than during TR. Since $\dot{V}O_2max$ in DWR was not measured in this study, the extent of the relative percentage differences is not known. Another plausible explanation for the higher RPE responses during DWR may be the greater involvement of the relatively untrained arms. During TR, the arms swing through air, whereas during DWR they swing through water, which imposes greater resistance to movement. The legs encounter greater resistance to movement, too, but they are also relieved of a weight-bearing load. Thus, even though the subjects are working at the same absolute $\dot{V}O_2$, it would be reasonable to conclude that the arms are contributing more to the oxygen cost, and the legs less, during DWR than during TR. This shift in the responsibilities of the arms and legs during DWR, as compared to TR, has also been described by Michaud and coworkers (24). A greater involvement of the less well-trained and smaller muscle groups of the arms may be a factor in the higher RPE values found during DWR (7).

Figures 2 and 3 provide qualitative evidence that the choice to focus on XY displacement, especially at the ankle (Figure 3), during DWR and TR is more useful when determining kinematic differences between styles of running. These figures graphically illustrate that the CC style of DWR bore distinct similarities to TR, particularly with respect to horizontal displacement. However, the vertical differences exhibited in the figures between land-based running and the CC style are explained by the assistance force of buoyancy in DWR, which allows the knee to lift higher than would be normal in TR. Treadmill running also has a ground contact period and is affected by gravity. The ground contact may be apparent in the graphs of the knee (Figure 2), where the displacement curve follows a somewhat equal path both anteriorly and posteriorly, and exhibits a minor depression in the middle of the curve, which corresponds with foot strike, whereas this is less true in the DWR curves. After full extension of the leg and prior to flexion, drag on the lower leg and the resistance force of buoyancy (17) act on the distal end of the lower extremity during DWR to produce hyperextension of the knee during the CC style of DWR (CC: $-7.51 \pm 5.4°$). This finding has ramifications primarily for DWR injury rehabilitation of the knee. It is advisable to caution the deep-water runner to limit the full extension of the leg. This should decrease the likelihood of possibly causing more harm while using the CC style of DWR. Additionally, this knee hyperextension is also likely to be a manifestation of a longer period of the gait cycle occurring in front of the hip than is found during TR. This observation is corroborated by the descriptive joint angle data for the hip in this study (TR: $-13.6 \pm 5.6°$; CC: $11.81 \pm 9.6°$).

The differences between DWR styles and TR found in the illustrations would not have been as apparent had we used the more typical approach of analyzing the minimum and maximum joint angles. Based on these illustrations, it may be argued that the CC style of DWR appears to better satisfy the specificity-of-training principle with respect to a closer simulation of land-based running lower-extremity kinematics (7, 24). Statistical analyses of the kinematic data support these observations (Tables 5–9). Both the minimum and the maximum horizontal ankle displacements (Table 6) for CC DWR did not differ from those for TR. On the other hand, it may be contended that the CC style elicits a more generalized and balanced workload throughout the lower extremities. This contention is supported by the fact that the leg will be exposed to an increased amount of resistance (drag), in large part because of an increased total amount of surface area exposure within a more viscous fluid environment. This also explains the slower SR of the CC style (64.8% of TR). Regardless of SR and lower-extremity kinematics, however, an equivalent metabolic cost ($\dot{V}O_2$) can be attained, though at a slightly higher RPE when in water.

Figures 2 and 3 further provide qualitative evidence that the HK style of DWR follows a pronounced vertical path with very little horizontal positional change. Statistical analyses of the kinematic data support these observations (Tables 5–9). Both the minimum and the maximum horizontal ankle displacements (Table 6) for HK DWR differ from those for TR. Furthermore, it has been reported that with the limited range of motion of the HK style, there appears to be an increase in localized muscular fatigue in the quadriceps, hip flexors, and deltoids (7). With respect to SR, HK DWR exhibited a smaller difference from TR (91.2%) than did the CC style. However, the faster SR is accomplished by reducing the resistance encountered by moving through a limited range of motion.

A strength of this study was that the physiological and kinematic responses to TR and the 2 most common forms of DWR (CC and HK) were evaluated in the same project, and, in addition, they were compared at the same absolute level of oxygen consumption. Furthermore, this study advanced the kinematic analysis of DWR by examining XY linear displacement (positional) values of the lower extremities, which provide a more informative and practical baseline representation of range of motion during the running gait than do joint angle minimum and maximum data, which have more typically been presented (13, 25). Using pilot data, it was determined that the more commonly reported joint minimum and maximum angles would not adequately differentiate running styles with respect to range of motion. Furthermore, analyzing velocities (28) between inherently different media (air and water) would not provide as clear a comparison between TR and DWR kinematics as using linear lower-extremity data to differentiate DWR techniques.

A limitation of the study is that kinematic data describe the movement patterns and rates, but electromyographic data would be necessary to compare the timing and magnitude of muscle recruitment to accomplish the movements (21, 26). This is relevant when comparing movements performed in air to those in water, which offers both assistance and resistance buoyancy effects.

PRACTICAL APPLICATIONS

As an adjunct form of distance running training or rehabilitation, the 2 forms of DWR styles (CC and HK) offer different forms of overload. If the desired effect of DWR is to best mimic TR relative to linear range-of-motion movement specificity and to thus possibly satisfy the specificity-of-training principle, the CC style is recommended. However, if the desired effect is to provide a physiological stimulus by emphasizing stride cycle rate irrespective of linear range of motion, the HK style is a closer approximation of TR. It appears that either style will provide physiological benefit to the runner. Just as is true with land-based programs, e.g., running mechanics drills, the practitioner is encouraged to provide appropriate instruction and feedback to the deep-water runner to insure proper mechanics.

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