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Optimization and Reliability of a Deep Water Running Test in Healthy Adults Older than 45 Years

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ABSTRACT

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Objective: The aim of this study was to (1) compare the peak oxygen uptake across three protocols of different duration during an incremental deep water running test to exhaustion; (2) study the reproducibility of peak $\dot{V}O_2$ during two repeated incremental deep water running tests; (3) compare peak deep water running test and treadmill cardiopulmonary responses in adults older than 45 yrs.

Design: First, 24 healthy subjects older than 45 yrs (60 yrs [6 yrs], body mass index: 28 kg/m^2 [6 kg/m^2], 11 men/13 women) performed three incremental deep water running tests ($\leq$8 mins, 8–12 mins, and $\geq$12 mins) with measurement of peak $\dot{V}O_2$ (optimization group). Nineteen subjects of the 24 original subjects (reproducibility group) then performed two repeated maximal deep water running tests. Finally, 21 of the 24 original subjects also performed an additional maximal treadmill test (comparison group). Peak $\dot{V}O_2$ was compared with analyses of variance for repeated measurements for the optimization, reproducibility, and comparison groups.

Results: Peak $\dot{V}O_2$ (ml/min) did not differ according to protocol duration (short: 1529 [674]; intermediate, 1456 [594]; and long, 1465 [674] ml/min, $P = 0.53$), was reproducible with an intraclass correlation coefficient of 0.90 ($P < 0.0001$), and was lower compared with treadmill (deep water running test: 1615 [586] *vs.* T: 2545 [511] ml/min, $P < 0.0001$).

Conclusions: A 6- to 12-min protocol duration can be used to assess deep water running test peak $\dot{V}O_2$, which is reproducible and lower compared with that obtained on the treadmill in healthy subjects older than 45 yrs.

Key Words: Aqua Jogging, VO$_2$max, Protocol Duration, $\dot{V}O_2$ Plateau Incidence, Reproducibility

Arthritis, other rheumatic conditions, and musculoskeletal injuries represent a leading cause of morbidity in North America, leading to a high prevalence of physical disability in middle-aged and elderly populations.[1–3] The prevalence of arthritis has been estimated at 22% in the United States, leading to limitation of physical activity in ~8% of individuals.[1] A recent study[2] also suggests that musculoskeletal injuries can have a negative impact on short- and long-term activity levels in otherwise physically active adults. The assessment of peak cardiopulmonary responses may be difficult and/or impossible using conventional exercise testing (treadmill or cycling) for those individuals who are affected by arthritis and/or musculoskeletal conditions.

Deep water running (DWR) test is one alternative for maximal exercise testing and training in athletes, individuals with arthritis, musculoskeletal and/or mobility limitations, and particularly elderly populations.[4,5] DWR test is performed in the deep part of the swimming pool, where the individual attempts to reproduce the pattern of limb movements used when running on land or a treadmill.[6–8] Subjects wears a flotation vest maintaining the head out of the water, without contact with the swimming pool bottom, thereby reducing joint load and strain during exercise.[6–8] DWR test has been used in young athletes[9] and military recruits[10,11] as a training tool to maintain aerobic performance and reduce or prevent running injuries. Moreover, a DWR training program has been shown to improve maximal aerobic capacity in young sedentary subjects[12,13] and elderly women.[5]

Peak cardiopulmonary responses during DWR tests have been extensively studied in comparison with treadmill running in several sample groups including young physically active adults,[6–8,13–17] middle-aged men,[18,19] and elderly women.[4] Peak oxygen uptake during DWR has been found to be 8.1%–29% lower compared with peak oxygen uptake during conventional treadmill testing.[6–8,13–17,21] Previous studies, however, have used different protocols, making comparisons difficult. Several limitations can be noted including subjective exercise intensity increases,[8] discontinuous protocols without available data on stride frequency and exercise times,[4,5,7] use of the protocol by Wilder et al. without providing exercise time,[19,20] or only providing stride cadency.[10,18,19] Finally, in three studies with young active adults,[13–15] both exercise time and type of protocol used were indicated.

Protocol duration can influence peak oxygen uptake during an incremental test to exhaustion during conventional exercise testing using treadmill or ergocycle exercise testing.[21–23] As a result, protocols with exercise times of 6–12 mins are generally recommended to provide an optimal estimate of peak oxygen uptake in healthy individuals, independent of age and sex.[21–24] In contrast, the optimal protocol duration for an incremental DWR test has not been documented, particularly in older subjects where this test is of particular utility. Finally, although the reproducibility of the DWR test was found to be excellent in young adults for peak oxygen uptake and heart rate for two repeated DWR tests,[25] the reproducibility of the test has not been studied in older adults. To better standardize the DWR running test in adults (older than 45 yrs), we sought (1) to compare the effects of three different protocol durations (≤8 mins, 8–12 mins, and ≥12 mins) on peak cardiopulmonary responses ($\dot{V}O_2$, ventilation, and heart rate) and $\dot{V}O_2$ plateau occurrence during incremental DWR tests; (2) to study the reproducibility of peak cardiopulmonary responses ($\dot{V}O_2$, ventilation, and heart rate) during two repeated incremental DWR test in the same population; and (3) to compare peak cardiopulmonary responses ($\dot{V}O_2$, ventilation, and heart rate) measured during incremental DWR and treadmill tests.

METHODS

Subjects

The experiment complies with the current laws of Canada and was approved by the institutional Ethics Committee. A total of 24 healthy physically active subjects older than 45 yrs (11 men and 13 women; age, 46–73 yrs) were recruited at our institution. All individuals were members of the Cardiovascular and Prevention Centre (Centre ÉPIC) for at least 3 mos, engaged in physical activity on land or in water ~2–3 times per week and were accustomed to performing maximal exercise treadmill tests to assess functional capacity.[26] Exclusion criteria included participants younger than 45 yrs; had cardiovascular, pulmonary, or metabolic pathology; inability to perform a maximal cardiopulmonary exercise test; and inability to swim. The research protocol was approved by our institutional Ethics Committee, and written informed consent was obtained before study entry. Anthropometric and clinical data of the 24 subjects are presented in Table 1. Among all the participants, 21 subjects were unfamiliar with DWR activity when they were included in the study. History of musculoskeletal conditions encountered in some subjects (Table 1) was defined as pervious arthritis or musculoskeletal injuries documented in the patient's medical chart.

Study Procedures

At baseline, subjects were evaluated with measurement of weight, height, body composition, fasting lipid profile, resting ECG, and blood pressure. Body composition was measured by bioimpedance analysis to estimate lean body mass.[27] Before maxi-

TABLE 1 Anthropometric and clinical data of the three groups

Parameters	Optimization Group (n = 24)	Reproducibility Group (n = 19)	Comparison Group (n = 21)
Age (yrs)	60 (6)	60 (8)	60 (7)
Body mass (kg)	80 (19)	78 (16)	82 (20)
Height (cm)	166 (8)	166 (6)	167 (7)
Sex (n, male/female)	11 males/13 females	9 males/10 females	11 males/10 females
BMI (kg/m^2)	28.9 (6.0)	28.2 (5.8)	29.2 (6.0)
Fat mass percentage (%)	32 (7)	31 (7)	32 (7)
Fat mass (kg)	26 (10)	24 (8)	26 (10)
Lean body mass (kg)	53 (12)	52 (10)	54 (12)
Total cholesterol (mmol/liter)	5.00 (1.33)	5.16 (1.41)	5.07 (1.38)
HDL-cholesterol (mmol/liter)	1.45 (0.35)	1.49 (0.33)	1.48 (0.36)
LDL-cholesterol (mmol/liter)	3.00 (1.05)	3.13 (1.11)	3.05 (1.07)
Total cholesterol/HDL	3.50 (0.80)	3.48 (0.73)	3.47 (0.79)
Triglycerides (mmol/liter)	1.20 (0.60)	1.17 (0.60)	1.16 (0.63)
Triglycerides/HDL	0.91 (0.58)	0.84 (0.51)	0.87 (0.61)
β-blockers	2 (8.3%)	2 (10.5%)	1 (5.2%)
ACE inhibitors	1 (4.1%)	1 (5.2%)	1 (5.2%)
Antiplatelet agents	1 (4.1%)	1 (5.2%)	1 (5.2%)
AR blockers	3 (12.5%)	2 (10.5%)	3 (15.1%)
Statins	3 (12.5%)	1 (5.2%)	2 (10.5%)
Ca^{2+} blockers	2 (8.3%)	2 (10.5%)	2 (10.5%)
Diuretics	1 (4.1%)	0 (0%)	1 (4.1%)
History of musculoskeletal conditions	4 (16.6%)	1 (5.2%)	2 (10.5%)

Values are in means (SD) or n (%).

Optimization group included subjects who have participated in the short, intermediate, and long deep water running (DWR) protocols; reproducibility group included subjects who have participated in two repeated identical DWR protocols; and comparison group included subjects who have participated in a treadmill after their participation in the optimization and/or the reproducibility group.

ACE, angiotensin converting enzyme; AR, agiotensin receptors; HDL, high-density lipoprotein; LDL, low-density lipoprotein.

mal exercise testing, subjects were instructed to refrain from consuming alcohol or caffeine or smoking for at least 48 hrs and not to perform strenuous exercise for at least 12 hrs before testing.

Protocol Duration During DWR Tests

Twenty-four subjects composed the optimization group and were assigned to three visits to the swimming pool to perform the three maximal DWR protocols of different duration: the short DWR test ≤8 mins, the intermediate DWR test between 8 and 12 mins and the long DWR test ≥12 mins. The DWR protocols (S, short; I, intermediate; and L, long) were randomly assigned to subjects using the six sequences of possible DWR protocol arrangements (S-I-L, S-L-I, I-S-L, I-L-S, L-S-I, and L-I-S). Thus, there were four subjects per sequence, and each protocol was followed (or preceded) by the other two protocols the same numbers of times, minimizing possible comparison biases. Water temperature was stable during testing (30°C) and was in the thermoneutral zone.[28] Participants wore a flotation vest (Wet Vest II; HydoFit, Eugene, OR), were tethered with two elastic cords to the poolside to maintain a stationary position, and were immersed to neck level. The DWR technique was performed according to current recommendations[10] under supervision to ensure correct movement execution. In brief, subjects were instructed to develop a natural running motion with a vertical alignment of the body, a slight forward trunk inclination of 2–3 degrees in the sagittal plane and unilateral forward motion of the arms and legs. Arm movement occurred with the elbows held flexed (~90 degrees), with the palm of the hand closed. Hips and knees were flexed forward (~45–70 degrees for the hip and 90 degrees for the knee), with the legs then extended thereafter. Before the first test, subjects had a familiarization session lasting 5 mins to ensure proper execution of the DWR movement.

Exercise protocols (modified Wilder et al. protocol) began with a 2-min warm-up period at a running cadency of 56 cycles/min; cadency was then increased every 2 mins by 8–30 cycles/min imposed by a metronome,[29] depending on the protocol (short, intermediate, and long) until the subjects could no longer follow the pace (assessed by a kinesiologist familiar with DWR protocols) and/or until exhaustion (voluntary exercise cessation by the subject). Each subject had an individualized running cadency for each protocol duration; the minimal cadency was 8 cycles/2 mins, and the maximal cadency was 30 cycles/2 mins for the optimization group. During DWR tests, cardiopulmonary responses were measured with a portable telemetric gas analyzer (Cosmed K4b2; Cosmed, Rome, Italy) and a telemetric ECG system (Quark T12; Cosmed). Subjects wore a nose-clip and mouth adapter that was connected to the gas analyzer; this adapter increased the dead space by 80 ml, which was calibrated by the Cosmed K4b2 software. Cardiopulmonary responses were measured for 3 mins at rest, during the 2-min warm-up period, during the exercise phase, and for 5 mins during recovery. The calibration of the flow module was accomplished by introducing a calibrated volume of air at several flow rates with a 3-liter pump. Each gas analyzer was calibrated before each test using a standard certified commercial gas preparation (O_2: 16%; CO_2: 5%). Data were measured every four respiratory cycles during testing and then were averaged every 15 secs for minute ventilation (VE, liters/min body temperature and pressure, saturated), O_2 uptake ($\dot{V}O_2$, liters/min standard temperature and pressure, dry (STPD)), CO_2 production ($\dot{V}CO_2$, liters/min STPD), respiratory exchange ratio (RER), ventilatory equivalent for O_2 (VE/$\dot{V}O_2$), ventilatory equivalent for CO_2 (VE/CO_2), and respiratory frequency. DWR cardiopulmonary exercise tests lasted until the attainment of one of the two primary maximal criteria[21]: (1) a plateau of $\dot{V}O_2$ despite an increase in cadency, (2) RER >1.0, or one of the two secondary maximal criteria: (1) measured maximal heart rate attaining 95% of age-predicted maximal heart rate, (2) inability to maintain the running cadency, (3) patient exhaustion with cessation caused by fatigue or subjects or other clinical symptoms (dyspnea) or ECG abnormalities that required exercise cessation. The highest $\dot{V}O_2$ value reached during the exercise phase of each DWR test was considered as the peak oxygen uptake. $\dot{V}O_2$ plateau for each protocol was defined according to recent criteria[24]; an increase of $\dot{V}O_2$ values ≤50 ml/min during the last 30 secs. Each of the three tests was separated from each other by at least 1 day and <1 wk. After completion of the three different DWR tests, subjects were asked for the protocol they perceived as the most exhaustive.

DWR Protocols Reproducibility and Comparison

Nineteen of the original 24 subjects agreed to participate in the reproducibility phase of the study and were assigned to perform two additional maximal short DWR protocols. They all experienced at least three maximal DWR tests after their participation in the optimization group. The anthropometric and clinical data of the reproducibility group ($n = 19$) are given in Table 1. The short DWR test protocol (≤8 mins) was chosen because the highest mean absolute peak oxygen uptake values were observed with this test for the entire group (Table 2). The two repeated tests were sep-

TABLE 2 Peak cardiopulmonary data in 24 subjects older than 45 years obtained during the three different DWR protocol durations

Peak Parameters	Short Duration, ≤8 mins	Intermediate Duration, 8–12 mins	Long Duration, ≥12 mins	ANOVA and χ^2; *P* Values
VO_2 (ml/min)	1529 (674)	1456 (594)	1465 (674)	0.53
VCO_2 (ml/min)	1318 (525)	1336 (510)	1239 (477)	0.14
VO_2 (ml/min/LBM)	27.83 (8.03)	26.22 (7.04)	26.33 (8.1)	0.32
VE (liters/min)	68 (20)	70 (20)	69 (21)	0.62
RER	0.93 (0.09)	0.99 (0.16)	1.00 (0.14)	0.15
HR (beats/min)	139 (14)	141 (11)	135 (16)	0.04
O_2 pulse (ml O_2/pulse)	12.35 (6.0)	11.66 (5.02)	12.79 (6.20)	0.40
VT (L)	1.62 (0.45)	1.64 (0.44)	1.59 (0.41)	0.35
Rf (cycles/min)	42 (10)	42 (11)	41 (10)	0.35
VE/VO_2	39 (7)	42 (9)	39 (8)	0.11
VE/VCO_2	46 (10)	47 (10)	48 (10)	0.32
Exercise time (s)	442 (360–480)	619 (480–705)	832 (720–990)	<0.0001
Maximal running cadencies (beats/min)	136 (13)	133 (12)	131 (14)	0.02
VO_2 plateau (%)	58	83	62	a: $P = 0.058$ b: $P = 0.059$ c: $P = 0.76$

Values are in mean (SD) and mean and range unless noted otherwise.

VO_2 plateau was defined according to recent criteria.[24,31] The percentage of presence of a VO_2 plateau was performed using a χ^2 test of Mc Nemar. a: duration ≤8 mins *vs.* duration 8–12 mins; b: duration ≥12 mins *vs.* duration 8–12 mins; c: duration ≤8 mins *vs.* duration ≥12 mins.

LBM, lean body mass; VE, ventilation; RER, respiratory exchange ratio; HR, heart rate; VT, volume tidal; *Rf*, respiratory frequency.

arated by <1 wk, and comparison of the data were performed on the same exercise time. Because of musculoskeletal conditions and limitations, three patients did not participate in maximal treadmill testing. Therefore, 21 subjects (among the 24 subjects) were included in the comparison group and performed a maximal treadmill test with cardiopulmonary measurement after their participation to either the optimization or reproducibility group. During treadmill maximal tests, cardiopulmonary exercise testing data were measured with a portable telemetric gas analyzer (Cosmed K4b2) and a telemetric ECG system (Quark T12) with the same calibration procedure and data analysis described in the previous section. Based on the precedent treadmill metabolic equivalents value in the subject medical record,[26] the speed and grade were increased individually every 2 mins to obtain a maximal exercise time between 8 and 12 mins.[24,30] The mean initial speed and slope were 2.89 km/hr (SD = 0.35) and 2.42% (SD = 0.96), respectively, with a mean speed and slope increase (each 2 mins) of 0.6 km/hr (SD = 0.18) and 1.96% (SD = 0.5), respectively for the comparison group. Treadmill cardiopulmonary exercise tests lasted until the attainment of one of the two primary maximal criteria: (1) a plateau of $\dot{V}O_2$ ($\leq$50 ml/min during the last 30 secs) despite an increase in cadency, (2) RER >1.0, or one of the two secondary maximal criteria: (1) measured maximal heart rate attaining 95% of age-predicted maximal heart rate, (2) patient exhaustion with cessation caused by fatigue or subjects or other clinical symptoms (dyspnea), or ECG abnormalities that required exercise cessation. The highest $\dot{V}O_2$ value reached during the maximal treadmill tests was considered as peak oxygen uptake. $\dot{V}O_2$ plateau for each protocol was defined in the same manner according to recent criteria.[24,31] Each of the two tests (DWR and treadmill) was separated by <1 wk. The short DWR test protocol ($\leq$8 mins) was compared with the maximal treadmill test.

Statistical Analysis

All data are presented as means ± SD except otherwise indicated and were analyzed using Statview software (SAS version 5.0, Chicago, IL). Normality of data distribution was verified (Kolmogorov-Smirnov test), and no major deviations were found. One-way analyses of variance for repeated measurements were used for the optimization study ($n = 24$) subjects and the comparison study ($n = 21$). A post hoc test (Scheffé test) was performed to localize the differences. The percentage of presence of a $\dot{V}O_2$ plateau (plateau incidence in percent) for the three groups (optimization, reproducibility, and comparison) was compared using the McNemar χ^2 test. For the reproducibility group, intraclass correlation coefficients were calculated. A P value <0.05 was considered statistically significant.

RESULTS

Effects of Protocol Duration on Cardiopulmonary Data During DWR Tests

Peak cardiopulmonary response for the 24 subjects during the three different protocols (short, intermediate, and long) are presented in Table 2. There was no effect of protocol duration on peak cardiopulmonary response, except for the peak heart rate that was significantly lower during the long protocol, $\geq$12 mins relative to the two other protocols ($P < 0.05$). In addition, maximal running cadencies were lower on the long protocol ($P < 0.05$) compared with the short and intermediate protocols. Eight subjects (33.33%) attained their highest peak oxygen uptake during the short protocol ($\leq$8 mins), 8 (33.33%) during the intermediate protocol (8–12 mins), and 8 (33.33%) during the long protocol ($\geq$12 mins).

Incidence of $\dot{V}O_2$ Plateau During DWR Tests

The presence of a $\dot{V}O_2$ plateau tended to occur more frequently during the intermediate protocol relative to both the short ($\chi^2 = 3.60$, $P = 0.058$) and long protocols ($\chi^2 = 3.57$, $P = 0.059$) (Table 2). Subjects were also asked to subjectively rate the difficulty of DWR tests relative to each other and relative to maximal treadmill testing. DWR tests with the long protocol ($\geq$12 mins) were generally perceived as the most difficult.

DWR Reproducibility

Reproducibility data in the 19 subjects for the two repeated short DWR protocols are presented in Table 3. Peak cardiopulmonary responses were highly reproducible with high intraclass correlation coefficients for the main gas exchange data ($\dot{V}O_2$ in ml/min, $\dot{V}CO_2$ in ml/min, $\dot{V}O_2$ in ml/lean body mass/min) and ventilatory data (VE in liters/min, volume tidal in liters and respiratory frequency in cycles/min) ($P < 0.0001$). Among other parameters measured, RER, O_2 pulse (in ml O_2/pulse) and heart rate (in beats/min) showed less strong correlations.

DWR and Treadmill Comparison

Comparison of peak cardiopulmonary responses measured during the treadmill and DWR tests are presented in Table 4. Main peak cardiopulmonary responses obtained during treadmill were significantly higher compared with those obtained on the DWR (Table 4). The peak breathing frequency and $\dot{V}O_2$ plateau incidence were not different between treadmill and DWR tests (Table 4).

TABLE 3 Reproducibility of peak cardiopulmonary responses in 19 subjects older than 45 years during the two repeated short DWR test protocols

Peak Parameters	Test 1 (≤8 mins)	Test 2 (≤8 mins)	ICC	95% IC and χ^2, *P* Value
VO_2 (ml/min)	1486 (445)	1474 (446)	0.90	0.73–0.96, <0.0001
VCO_2 (ml/min)	1381 (457)	1436 (517)	0.92	0.81–0.96, <0.0001
VO_2 (ml/LBM/min)	28.9 (6.7)	28.8 (5.9)	0.84	0.64–0.93, <0.0001
VE (liters/min)	64 (18)	62 (20)	0.89	0.76–0.95, <0.0001
RER	0.99 (0.12)	1.01 (0.14)	0.65	0.30–0.84, 0.001
HR (beats/min)	138 (12)	136 (14)	0.70	0.38–0.87, <0.0001
O_2 pulse (ml O_2/pulse)	11.74 (3.81)	12.75 (5.37)	0.65	0.30–0.85, 0.001
VT (L)	1.67 (0.44)	1.66 (0.47)	0.93	0.83–0.97, <0.0001
Rf (cycles/min)	37 (8)	37 (11)	0.88	0.73–0.95, <0.0001
VE/VO_2	39 (7)	37 (8)	0.80	0.56–0.91, <0.0001
VE/VCO_2	43 (9)	40 (9)	0.74	0.45–0.89, <0.0001
VO_2 plateau (%)	47	63		$P = 0.5$

Values are in means (SD) unless noted otherwise. The percentage of presence of a VO_2 plateau was performed with a χ^2 test of McNemar.

ICC, intra-class correlation coefficient; IC, interval of confidence; LBM, lean body mass; VE, ventilation; RER, respiratory exchange ratio; HR, heart rate; VT, volume tidal; *Rf*, respiratory frequency.

DISCUSSION

The primary finding of this study is that protocol duration had no effect on peak oxygen uptake and peak cardiopulmonary responses (except for heart rate) during DWR tests in subjects older than 45 yrs. In addition, attainment of a $\dot{V}O_2$ plateau occurred with a similar frequency using all three DWR protocols, although there was a trend to more $\dot{V}O_2$ plateauing with the intermediate protocol relative to either short or long protocols. The second finding of this study is that peak oxygen uptake and peak cardiopulmonary responses were highly reproducible during two repeated DWR tests, establishing the reliability of this test for assessing peak cardiopulmonary responses in subjects older than 45 yrs. The third finding was that peak cardiopulmonary responses obtained during DWR test were lower than those obtained on treadmill. To our knowledge, no previous studies have assessed the effect of protocol duration on peak oxygen uptake and $\dot{V}O_2$ plateau occurrence using the DWR test in healthy adults during maximal exercise testing. Furthermore, this study is the first to report the reproducibility of peak oxygen uptake and peak cardiopulmonary responses performed during DWR tests in subjects older than 45 yrs.

Current recommendations for conventional exercise testing using treadmill or ergocycle generally use protocols lasting 6–12 mins duration to best approximate true maximal $\dot{V}O_2$ max values.[21–24]

TABLE 4 Peak cardiopulmonary data in 21 subjects older than 45 years obtained during the treadmill and DWR tests

Peak Parameters	Treadmill	DWR Test (≤8 mins)	ANOVA and *P* Values
VO_2 (ml/min)	2545 (511)	1615 (586)	<0.0001
VCO_2 (ml/min)	2853 (629)	1468 (442)	<0.0001
VO_2 (ml//LBM/min)	49.39 (14.4)	29.30 (8.12)	<0.0001
VE (liters/min)	80 (16)	69 (20)	0.0011
RER	1.09 (0.11)	1.01 (0.12)	0.0001
HR (beats/min)	154 (15)	138 (11)	<0.0001
O_2 pulse (ml O_2/pulse)	16.86 (4.02)	12.91 (5.64)	0.0045
VT (L)	2.29 (0.56)	1.70 (0.42)	<0.0001
Rf (cycles/min)	35 (7)	39 (9)	0.06
VE/VO_2	30 (7)	52 (22)	<0.0001
VE/VCO_2	28 (4)	44 (10)	<0.0001
VO_2 plateau (%)	47	66	0.34
Exercise time (secs)	572 (84)	479 (56)	0.0009

Values are in means (SD) unless noted otherwise.

LBM, lean body mass; VE, ventilation; RER, respiratory exchange ratio; HR, heart rate; VT, volume tidal; *Rf*, respiratory frequency.

However, no data exist on the optimal duration of the DWR test to maximize $\dot{V}O_2$. These results are in contrast with other studies that showed an effect of protocol duration on VO_2max with higher values for exercise times between 5 and 12 mins during treadmill or ergocycle evaluation.[21–24] Several potential mechanisms have been put forth to explain the lower VO_{2max} for land protocols lasting >12 mins. They include reduction of central cardiovascular function (cardiac output and stroke volume),[21,22] higher core temperature for longer exercise time,[21,22] ventilatory muscle fatigue,[22] and the subject's gender and/or fitness.[24] During DWR tests, several factors would seem to contribute to the lack of effect of protocol duration on peak oxygen uptake, as witnessed in the current study. First, peak oxygen uptake during DWR, already lower compared with treadmill running,[6–8,18,19,20] may be influenced by different physiologic determinants compared with conventional exercise modalities. A different recruitment of muscle groups during DWR (lower total muscle mass used) compared with land running has been given as a potential influence.[6–8,14–18] The arms assist the runner for buoyancy and encounter water resistance during DWR, and an increase of arm muscle work has been described.[13,18] Additionally, the hypogravitational effects of immersion could lead to reduced work of postural and leg muscles.[6–8] During water immersion, altered lung function during exercise has also been documented,[32,33] with hydrostatic pressure counteracting the inspiratory muscles, compressing the abdomen and raising the diaphragm, all of which result in reduced inspiratory force and vital capacity. Therefore, the cost of breathing is higher during water exercise, with slightly higher respiratory frequencies and reduced ventilatory efficiency ($VE/\dot{V}CO_2$).[32,33] In our study, peak ventilation during DWR tests was lower relative to peak values obtained on treadmill, and ventilatory efficiency was greatly reduced as indicated by high $VE/\dot{V}CO_2$ values >40 (Tables 3 and 4). During DWR tests, peak oxygen uptake may also be less dependant on the central cardiovascular response compared with conventional tests in which short protocol duration (5–6 mins) has been shown to maximize cardiac output.[23,34] We believe that maximal central cardiovascular responses during DWR were lower compared with land running because of the hypogravitational effects of water immersion, leading to the absence of foot contact and a support phase. This hypothesis is supported by lower peak heart rate and O_2 pulse during the DWR test compared with treadmill running.[7,14,19,20] In addition, previous studies have shown a lack of difference between peak oxygen uptake during cycling on land compared with during immersion,[20,35,36] indicating the importance of the exercise modality compared with the immersed state. Finally, the important variation of the energetic cost of movement during DWR can also be put forth to explain the lack of effect of protocol duration on peak oxygen uptake. Two previous studies have explored the energetic cost of movement during DWR in young athletes[37] or in older aged male runners.[18] Both showed a higher variation of the energetic cost of movement during DWR compared with treadmill running.[18,37] The lower peak heart rate observed with the long DWR protocol is in disagreement with the study of Astorino et al., which was however performed on a treadmill; a higher peak heart rate for the long protocol (>12 mins) *vs.* the intermediate (8–12 mins) and short (<8 mins) protocols was observed. Although we do not have an objective explanation for this result (lower heart rate for the long protocol), biological variability, and small sample size may be implicated.

Incidence of $\dot{V}O_2$ Plateau During Maximal DWR Tests

Our results concerning the presence of a $\dot{V}O_2$ plateau are in the range of previous data using conventional exercise testing (treadmill and cycling) where the incidence of $\dot{V}O_2$ plateauing ranged from 33% to 94%[30] depending on plateau criteria used, protocol, study sample, and $\dot{V}O_2$ uptake averaging. Our results are consistent with those of Phillips et al.,[38] which reported a plateauing of $\dot{V}O_2$ in 78% of overweight women during maximal DWR tests, but their $\dot{V}O_2$ plateau criteria was less strict. Furthermore, our data concur with the previous data obtained on a treadmill with the same methodology, in women with an 8-min protocol[24] and in men and women with an 8- to 12-min protocol.[39] Finally, Yoon et al. showed a lower $\dot{V}O_2$ plateau incidence on treadmill in healthy men (37.5% plateau incidence with 8-min protocol and a 25% plateau incidence with a 12-min protocol).

DWR Reproducibility

In this study, the DWR test showed excellent reproducibility for peak cardiopulmonary responses, particularly with respect to absolute $\dot{V}O_2$ uptake (ml/min, intraclass correlation = 0.90) or normalized by lean body mass (ml/min/lean body mass, intraclass correlation = 0.84). This result confirms the reliability of the DWR test in assessing peak oxygen uptake and peak cardiopulmonary responses in subjects older than 45 yrs. This test is of great potential utility because of the higher prevalence of arthritis, rheumatic, and musculoskeletal conditions,[1–3] which can limit the assessment of peak cardiopulmonary function during conventional exercise testing on land. To our knowledge, only one study has assessed the reproducibility of cardiopulmonary responses during the DWR test, and this was performed in young adults $<$30 yrs.[25] Mercer and Jensen[25] reported an intraclass correlation coefficient of 0.96 and 0.97 for peak oxygen uptake (in liters/min and ml/min/kg, respectively) and 0.9 for peak heart rate. These values are slightly higher than the ones reported in our study, potential reasons for these differences being a different DWR protocol, a more homogenous and younger age (mean age: 24 yrs) and a higher and more homogeneous physical fitness level in the study by Mercer and Jensen.[25]

DWR and Treadmill Comparison

In agreement with previous studies comparing peak cardiopulmonary responses of DWR and treadmill in young adults[6–8,13–17,20] and older adults,[4,18,38] our study demonstrated significantly lower peak cardiopulmonary responses (−10%–36% depending on the parameter) on DWR compared with treadmill. In particular, peak oxygen uptake was 36% lower during DWR testing relative to treadmill tests in our subjects: this difference was greater than that previously reported in older populations.[4,38] Biomechanical factors such as the muscle force required to overcome water viscosity friction, particularly at maximal DWR cadencies, and different muscle group activation patterns may have contributed to the reduction of peak oxygen uptake.[7] We also observed lower peak ventilatory parameters (VE: −13% and volume tidal: −25%) and ventilatory efficiency (VE/$\dot{V}\text{CO}_2$: −36%) during DWR relative to treadmill tests, which may be explained by water pressure exerted on the chest that increases the force required during inspiration.[19] The reduction of peak ventilation (compared with treadmill) has been previously documented during DWR exercise, in association with a lower RER,[4,6,38] as shown in our results. Moreover, DWR peak heart rate and O_2 pulse were lower in our study (−10% and 23%) in accordance with previous studies in young[6–8,13–17,20] and other adults.[4,38] During immersion, a portion of total blood volume is redistributed to the heart, which increases cardiac blood volume, leading to a higher stroke volume and lower heart rate during water exercise compared with land exercise.[4]

CONCLUSION

This study demonstrates for the first time that protocol duration has no effect on peak oxygen uptake and peak cardiopulmonary responses (except for heart rate) in adults older than 45 yrs during DWR tests. We also report that $\dot{V}\text{O}_2$ plateauing occurred to a similar degree with all three DWR protocols, although plateauing tended to occur more often in the intermediate protocol compared with the long and short protocols. We also demonstrate that the DWR test showed high reproducibility of peak cardiopulmonary responses during two repeated tests in older adults. As expected, peak cardiopulmonary responses were lower compared with the treadmill values, and caution must be taken not to compare DWR values with norms obtained on the treadmill. Based on our findings, an optimal DWR test for use in middle-aged and elderly individuals is an incremental test lasting 6–12 mins so as to optimally assess peak oxygen uptake and cardiopulmonary function. The DWR test is also reliable for the evaluation cardiopulmonary function in older adults and is of great potential utility in those with musculoskeletal or other conditions making conventional exercise testing unsuitable.

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