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Research article

EXPLANATORY VARIANCE IN MAXIMAL OXYGEN UPTAKE

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ABSTRACT

The purpose of this study was to develop a prediction equation that could be used to estimate maximal oxygen uptake (VO_{2max}) from a submaximal water running protocol. Thirty-two volunteers (n =19 males, n = 13 females), ages 18 – 24 years, underwent the following testing procedures: (a) a 7-site skin fold assessment; (b) a land VO_{2max} running treadmill test; and (c) a 6 min water running test. For the water running submaximal protocol, the participants were fitted with an Aqua Jogger Classic Uni-Sex Belt and a Polar Heart Rate Monitor; the participants' head, shoulders, hips and feet were vertically aligned, using a modified running/bicycle motion. A regression model was used to predict VO_{2max}. The criterion variable, VO_{2max}, was measured using open-circuit calorimetry utilizing the Bruce Treadmill Protocol. Predictor variables included in the model were percent body fat (% BF), height, weight, gender, and heart rate following a 6 min water running protocol. Percent body fat accounted for 76% (r = -0.87, SEE = 3.27) of the variance in VO_{2max}. No other variables significantly contributed to the explained variance in VO_{2max}. The equation for the estimation of VO_{2max} is as follows: VO_{2max} $ml \cdot kg^{-1} \cdot min^{-1}$ = 56.14 - 0.92 (% BF).

KEY WORDS: Water running, body composition, maximal oxygen uptake, body fat.

INTRODUCTION

The wide use of water exercise, specifically water running, as an effective rehabilitation therapy is well documented, it serves the needs of a wide variety of clinical conditions ranging from young athletes and recreational exercisers who suffer from lower extremity injuries to older individuals who have had hip or knee replacements (Ehrman et al., 2003; Hertling and Kessler,1996). Other pathological conditions served by this rehabilitative medium include but are not limited to obesity, arthritis, and peripheral vascular disease (American College of Sports Medicine, 2002). Water running is also a popular water based fitness medium for recreational fitness enthusiasts of all ages (Gehring et al., 1997; Reilly et al., 2003; Yamaji et al., 1990). However, there are no published submaximal running water protocols that can be used to predict maximal oxygen uptake ($VO_{2\ max}$) and therefore be used to document observed outcomes. Outcomes have been defined as the end result of medical interventions and processes (Jenkinson, 1994) or a change in the health of an individual which is attributable to an intervention or series of interventions (New South Wales, 1992). Outcome assessments following a rehabilitation program are becoming increasingly important in health care reimbursement decisions. Ideally, the testing protocol used as an assessment tool to document outcomes following an intervention program should closely represent the training environment (Wilmore and Costill, 2003).

Even though the open-circuit calorimetry or direct measurement of $VO_{2\ max}$ has been recognized as the most accurate method of evaluating cardiorespiratory fitness, the method is laborious and intricate, and can only be performed in a well-equipped laboratory. These limitations have led to the development of a variety of protocols to predict VO_{2max} from a submaximal effort. In the aquatic environment, the most widely used submaximal test is the 12 min swimming test (Conley et al., 1991). In addition to the time constraints imposed by this test, a lap pool is needed for testing, and the test depends heavily on swimming stroke skill.

Given the popularity of water based fitness and rehabilitative training programs and the concomitant lack of published submaximal water tests to predict VO_{2max}, the purpose of this study was to design a submaximal water running protocol using theoretical variables to predict VO_{2max} and to minimize confounding variables that would affect the heart rate response in the water, as speculated in the literature. While it is widely accepted that heart rate response to submaximal land exercise is a valid and reliable predictor of VO_{2max}, water exercise heart rate responses are confounded by many variables including but not limited to the temperature of the water, the depth of the water, mechanical efficiency, stride frequency, body surface area, whether or not the participant was wearing a flotation device, and the body composition of the participant (Costill et al., 1967; Pohl and McNaughton, 2003; Reilly et al., 2003; Town and Bradley, 1990; Yamaji et al., 1990). Therefore, these variables must be considered in the research design.

Based on the review of literature, it was hypothesized that VO_{2max} could be predicted from a submaximal water running protocol using water heart rate as a predictor variable, however, variables which could have an affect on heart rate must be included in the research design (Arborelius et al., 1972; Costill et al., 1967; Gleim and Nicholas, 1989; McCardle et al., 1976; Pohl and McNaughton, 2003; Reilly et al., 2003). It was postulated that the variables that would increase the power of the prediction equation would be the participant's exercise heart rate at the end of a 6 min water running protocol, percent body fat (% BF), height, weight, and gender (Arborelius et al., 1972; Brown et al., 1998; Costill et al., 1967; Gleim and Nicholas, 1989; Jackson et al., 1990; Jones, 1997; Kaminsky et al., 1993; Kline et al., 1987; McCardle et al., 1976; Pohl and McNaughton, 2003; Reilly et al., 2003).

METHODS

Selection and description of participants

Following approval from the institutional review board at Texas Tech University (TTU), participants were recruited from the general population of college students in the Personal Fitness and Wellness classes offered by the Department of Health, Exercise, and Sport Sciences at TTU. All participants signed an informed consent as approved by the TTU University Institutional Review Board. In order to be a participant in the study, participants had to be considered apparently healthy as defined by the American College of Sports Medicine (2006). Following the screening criteria, 32 volunteers (n = 19 males, n = 13 females), ages 18–25 years, participated in the study. The participants had not been trained in water running and would be considered novice water runners.

Technical information

Participants underwent the following testing procedures: (a) a 7-site skinfold assessment; (b) a VO_{2max} land treadmill test; and (c) a 6 min water running test. All testing was completed over a 2 day period. The first day of testing consisted of skinfold assessments followed by VO_{2max} testing. The VO_{2max} exercise treadmill test on land and the water running protocol were separated by at least a 24 hour period. Day 2 consisted of a 6 min water running test. Participants were asked to refrain from food, alcohol, or caffeine or using tobacco products within 3 hours of testing.

Skinfold assessment: A Lange Skinfold caliper (Cambridge Scientific Industries, Inc.; Cambridge, Maryland) was used to obtain skinfold measurements using standardized procedures (American College of Sports Medicine, 2006). A gender-specific 7-Site formula was used to determine body density (Jackson and Pollock, 1985). Body composition was estimated from body density using the Siri (1961) equation.

Maximal oxygen uptake: The Quinton treadmill (Quinton Instrument Company; Seattle, Washington) was used for VO_{2max} testing utilizing the Bruce Protocol on land. A Quinton Electrocardiogram (ECG) Monitor (Quinton Instrument Company; Seattle, Washington) was used to determine heart rate and monitor heart rhythm during the VO_{2max} test. A metabolic measurement system, CPX/D, (Med Graphics Corporation; St. Paul, MN) was used to measure VO_{2max}. For the purposes of this study, VO_{2max} was expressed in relative terms ($ml \cdot kg^{-1} \cdot min^{-1}$). The metabolic measurement system was interfaced with the Quinton ECG for heart rate during testing. All equipment was calibrated prior to testing. Volume calibration of the pneumotach was made utilizing a 3-liter syringe. Gas analyzer was calibrated with the use of certified reference gas tanks.

Prior to beginning the test, participants were instructed to stretch their lower extremity muscles, particularly their gastrocnemius. Participants' rate of exertion as perceived on the Category-Ratio Borg scale, blood pressure, ECG, and heart rate were monitored and recorded at the end of every 3-min stage during the VO_{2max} test. Absolute and relative indications to stop an exercise test were followed as outlined by ACSM (2006). The test was terminated when the participant could no longer continue to voluntarily exercise. A respiratory exchange ratio in excess of 1.00 was also used as an indicator of maximum achieved effort (McArdle et al., 2001). Recovery heart rate and blood pressure were collected for 8 min or until the pre-test baseline was present.

Water running protocol: The submaximal water running protocol was conducted in the Applied Physiology Lab in the Exercise Science Center on the Texas Tech University Campus in a fiberglass tank (128 cm in diameter, 402 cm in circumference, and 165 cm in depth). The depth of the water was constant given that research has found that the work of running in water is different at different depths (Pohl and McNaughton, 2003). The submaximal water running protocol was conducted in thermoneutral water temperature (33.9 °C ± 0.4) since studies have found that heart rates in thermoneutral water temperature (33-35˚C) are not significantly different from that on land during moderate exercise (Arborelius et al., 1972; McCardle et al., 1976; Noakes, 2002; Reilly et al., 2003). An Aqua Cal Digital Thermometer (Swim Things; Blue Springs, Mo.) was used to record the water temperature during testing. Participants were fitted with an Aqua Jogger Classic Uni-Sex Belt (Recreonics; Louisville, KY) and a Polar Heart Rate Monitor (Polar Electro Oy; Finland) during the submaximal water running protocol.

A specific running pattern as described was practiced by the participants prior to the actual test date. During the submaximal water running protocol, the participants' head, shoulders, hips and feet were vertically aligned, using a modified running/bicycle motion. The participants were instructed to alternately move each hip joint to a flexed position of 45° and a hyperextended position of 10° (Brown et al., 1997). The arms were not used during testing except to lightly touch a bar anchored in the middle of the tank in order to prevent forward movement.

Assumptions for submaximal testing were considered in the protocol design and testing procedures (American College of Sports Medicine, 2006). The test was designed similarly to the Astrand-Rhyming 6 min submaximal cycle ergometer test in which the heart rate at the end of the 6 min test was plotted against workload to estimate VO_{2max} (Astrand and Ryhming, 1954). For submaximal efforts a steady-state heart rate is achieved within 1-2 min, therefore, each stage in the protocol was 2 min (American College of Sports Medicine, 1986; Wilmore and Costill, 2003). The testing protocol consisted of 3 stages, for a total test time of 6 min. During the first 2 min stage, the participants were asked to run at a cadence of 100 beats per min (bpm). During the second 2 min stage, the cadence increased to 108 bpm, and during the last stage the cadence increased to116 bpm (Brown et al., 1997). A metronome (Seiko Quartz; Timberlake, NC) was used to designate the running motion frequency and to regulate the net oxygen cost of the exercise by imposing an externally controlled cadence. Heart rate was recorded from the Polar Heart Rate Monitor at the end of each 2 min stage in order to determine heart rate response while exercising in the water.

Data analysis

All data were analyzed using the SPSS Statistical Data Analysis System (SPSS; Chicago ILL). Descriptive statistics computed for each study participant (n = 32) included gender, age, weight, height, %BF, VO_{2max}, and heart rate taken at the end of the 6 min water running protocol. Hypothesized predictor variables (gender, weight, height, % BF, and heart rate at the end of the 6 min water running protocol) were included in a Pearson Product Moment Correlation Matrix to quantify the independence of the predictor variables**.** Variables with a moderate correlation of .5 were scrutinized by the researcher before being included in the full model (George and Mallery, 2000; Hinkle et al., 2003). Gender and height (r = 0.63) and height and weight (r = 0.56) were examined for theoretical inclusion in the model. Based on previous research, these variables were included in the model (Jones, 1997; Kaminsky et al., 1993; Kline et al., 1987).

The criterion variable in the equation was the participants' measured VO_{2max} on land expressed in relative terms ($ml \cdot kg^{-1} \cdot min^{-1}$). The predictor variables included in the equation were the participants' gender, weight, height, % BF, and heart rate at the end of the 6 min water running protocol. Based on the information from the full model, a restricted model was run using only the variables that significantly contributed to the variance in VO_{2max}. A p value < 0.05 was used as the criterion for inclusion in the restricted model. Only the variable, % BF was included in the restricted model. A test of R^2 change was then calculated between the R^2 values for the full and the restricted models in order to test for the difference between the variance explained by the restricted and full models.

RESULTS

Descriptive statistics for the participants are shown in Table 1. The full multiple regression model is shown in Table 2. The difference between the full model and the restricted model was not statistically significant. The critical *F* value needed was 2.74, and the calculated *F* was 0.94. The most efficient and explanatory model was the single variable model (r = -0.87, *SEE* = 3.27). The coefficient of determination for this model was 0.76, therefore, % BF accounted for 76% of the variance in VO_{2max}. The adjusted R^2 which takes account the number of variables are in this model was 0.75 (df = 1, 30). (The regression equation is as follows: VO_{2max} ml·kg^{-1}·min^{-1} = 56.14 - 0.92 (% BF).

Table 1. Descriptive data for the participants. Data are means (±SD).

Variables	Males (n = 19)	Females (n = 13)
Age (yrs)	20.8 (1.7)	20.8 (1.8)
Height (m)	1.80 (.06)	1.69 (.09)
Weight (kg)	76.6 (13.4)	64.9 (12.3)
Body Fat (%)	12.7 (7.0)	18.0 (3.0)
*Heart Rate	156 (17)	149 (14)
†$VO_{2\ max}$	45.1 (6.7)	38.7 (4.2)

* Heart Rate is heart rate at the end of a 6 min water running protocol in beats per min.
†$VO_{2\ max}$ = maximal oxygen uptake (ml·kg^{-1}·min^{-1}).

DISCUSSION

In our study we used the land treadmill utilizing the Bruce Protocol as the criterion variable for VO_{2max}. The highest value for VO_{2max} has been found using a running test up a grade on a land treadmill (ACSM, 2006; Barnard et al., 1973; Powers and Howley, 2004); therefore, this was considered the best choice to assess VO_{2max}. Similarly, other water running prediction protocols have also used the graded exercise test on land using open-circuit spirometry as the criterion variable for VO_{2max} (Kaminsky et al., 1993).

The Bruce Protocol was chosen because it meets the criteria established by ACSM for graded exercise tests and is well suited for young healthy individuals (ACSM, 2006). Also, the Bruce Protocol has yielded similar peak VO_2 values than less intense protocols and has been found to be more time efficient (Strzelczyk et al., 2001). It also is thought that bicycle exercise protocols may underestimate peak VO_2 in some populations (Barnard et al., 1973; ACSM, 2006).

Since we used college age students, the results of our study should be extrapolated to rehabilitation settings where the population is young and recreationally fit. Recreational exercisers who suffer from lower extremity injuries would fall in this category. However, the subject pool could be a limitation in our study since the water running protocol would be an ideal assessment medium for the elderly, who may have had hip or knee replacements, or who may suffer from arthritis and peripheral vascular disease, as well as the obese patient. Therefore, these clinically relevant populations should be used in the study in order to extrapolate the findings to these specific populations.

Also our population was not skilled in water running. In hindsight, this is a limitation in the study design. It is speculated that during the water running protocol, individuals with low skill level in water running, simply shortened their stride length to maintain the desired rate of leg alterations or to avoid the onset of fatigue as the workload increased (Glass, 1987). At the end of each continuous stage, the cadence increased by 8 bpm. Heart rates at 100, 108, and 116 bpm were 131, 145, and 153, respectively. Even though the increase in cadence was constant in both stages, the increase in heart rate from stage 2 to 3 was not as great as the increase in heart rate from stage 1 to 2. There was a 9% (14

Table 2. Full multiple regression analysis model.

Variable	Beta coefficient	t-value	Probability
Gender	-1.79	-.84	.41
Height	.10	.80	.43
Weight	-3.67	-.34	.73
Heart Rate	-3.64	-.87	.39
Body Fat	-.77	-3.48	.00
df = (1, 26)			
SEE = 3.31			
Intercept = 44.96			
R^2 = .79			
*Adjusted R^2 = .75			

* The adjusted R^2 takes into account how many variables are included in the estimation and slightly lowers the estimate of explained variance.

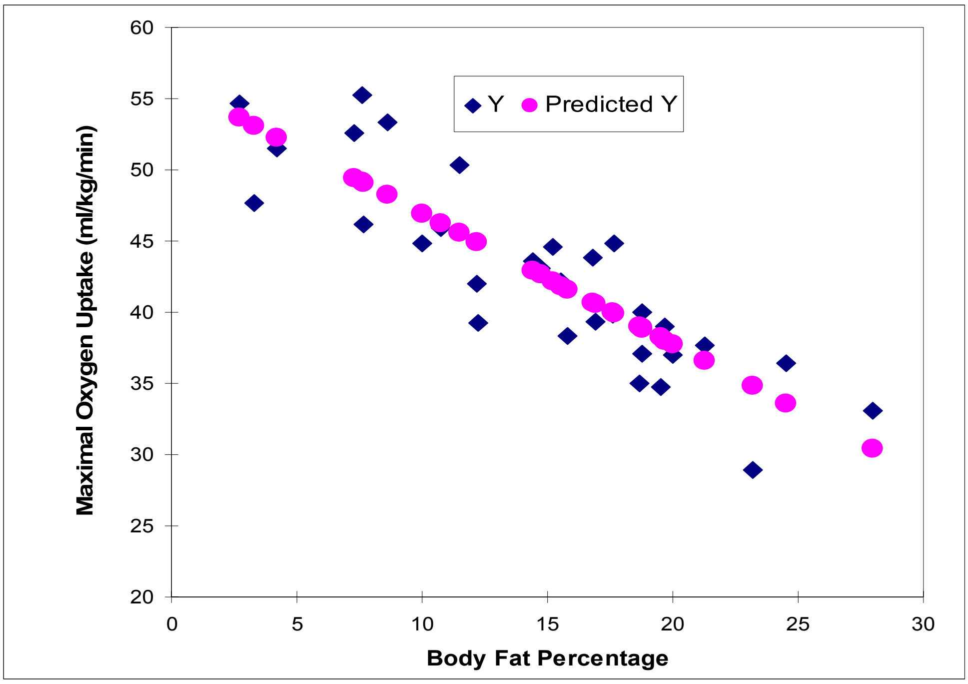

Figure 1. Relationship between body fat percentage and maximal oxygen uptake [VO_{2max} ml·kg^{-1}·min^{-1} = 56.14 - .92 (% BF)] (r = -0.87, SEE = 3.27).

bpm) increase in heart rate from stage 1 to 2, but only a 5% (8 bpm) increase from stage 2 to 3, suggesting that stride length was being altered. A running pattern that was not uniform or rather a difference in the range of motion at the same externally imposed cadence would have an effect on the net oxygen cost of the exercise by varying the water resistance to locomotion (Pohl and McNaughton, 2003). Therefore, water heart rate could not be used as a predictor variable in this group of unskilled water runners. In this experiment, it is hypothesized that heart rates accurately reflected the net oxygen cost of the exercise at the end of the 6 min water running protocol, as others have postulated (Gleim and Nicholas, 1989; Pohl and McNaughton, 2003; Reilly et al., 2003), but that the net oxygen cost of the exercise was different among participants depending on their mechanical efficiency (VO_2 at a given work rate). Future studies should use participants trained in the mechanics of water running to increase mechanical efficiency and maintain a uniformed running motion throughout the water running protocol.

Similarly to Kaminsky et al. (1993), we found that water heart rate did not significantly contribute to the explanatory variance in $VO_{2\ max}$, but that body fat was an important predictor variable to $VO_{2\ max}$. Others have also noted a decrease in $VO_{2\ max}$ with increases in adiposity (Ogawa et al., 1992). The physiological basis for the inverse relationship % BF and $VO_{2\ max}$ (see Figure 1) is the direct link between skeletal muscle mass and its capacity for generating oxygen demand and or consuming oxygen (Toth et al., 1993).

An advantage of our findings, comparable to others reported in the literature, is that the correlation coefficient is higher (r = -0.87), thus the explained variance is higher, and the SEE (3.27 ml·kg^{-1}·min^{-1}) is less, increasing the accuracy of the prediction equation. In our experiment, a single variable model, % BF, explained 76% of the variance in VO_{2max}. [VO_{2max} ml·kg^{-1}·min^{-1}= 56.14 - 0.92 (% BF)]. Clinicians and practitioners can go to www.hess.ttu.edu/mccomb to download a program which computes BF% and VO_{2max} ml·kg^{-1}·min^{-1} using this regression equation after inserting the skinfold thickness for the appropriate 7-sites depending on gender.

Kaminsky et al. (1993) reported a correlation coefficient of -0.82 between VO_{2max} and % BF in 43 volunteers (28 male, 15 female) from several university aqua-aerobics classes. Getchell et al. (1977) and Harrison et al. (1980) showed moderate to high correlation coefficients between VO_{2max} and % BF, r = -0.75 and r = -0.79, respectively. Jackson et al. (1990) developed a non-exercise prediction equation using the variables: activity status, age, % BF, and gender. These combined variables explained only 67% of the variance in $VO_{2\ max}$ (r = 0.81, SEE = 5.3).

CONCLUSION

A significant contribution of our study is the knowledge gained from the study and the generation of an idea for future applied research that has a practical application in clinical and fitness settings. A water running protocol would be a useful benchmark for individuals who train regularly in water running or use water running as a rehabilitative medium, therefore, the need for this protocol still exists in the research literature. However, future studies should use participants trained in the mechanics of water running to increase mechanical efficiency and maintain a uniformed running motion throughout the entire water running protocol, thus minimizing the variability in the net oxygen cost of the exercise. It is also recommended that $VO_{2\,max}$ be measured in the water as well as on land as a criterion reference.

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KEY POINTS

- Body Fat is an important predictor of VO_2 max.
- Individuals with low skill level in water running may shorten their stride length to avoid the onset of fatigue at higher work-loads, therefore, the net oxygen cost of the exercise cannot be controlled in inexperienced individuals in water running at fatiguing workloads.
- Experiments using water running protocols to predict VO_{2max} should use individuals trained in the mechanics of water running.
- A submaximal water running protocol is needed in the research literature for individuals trained in the mechanics of water running, given the popularity of water running rehabilitative exercise programs and training programs.

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