Research in Sports Medicine 11: 63–78, 2003

ISSN:1543-8627 print / 1543-8635 online
DOI:10.1080/154386203902274042

The Physiological Responses to Running and Walking in Water at Different Depths

MICHAEL B. POHL

University of Bath

LARS R. McNAUGHTON

University of Hull

Exercise in an aquatic environment may be an effective mode of therapy and training due to reduced impact forces. The purpose of this study was to compare the physiological responses of walking/running on a land treadmill with water treadmill responses at two different depths. Six subjects completed walking and running trials on both a land-based and a water-based treadmill. Water-based trials were completed in both thigh- and waist-deep water. Each trial was five minutes in duration. Oxygen uptake (VO_2), heart rate (HR), respiratory exchange ratio (RER), stride frequency (SF), and the oxygen cost per stride (VO_2/stride) were compared between the conditions using a two-way ANOVA with repeated measures. Walking and running in water elevated VO_2 ($p \leq 0.02$) and HR ($p \leq 0.04$) above land treadmill values. When running in waist-deep water, VO_2 and HR failed to increase to the same extent as thigh-deep running. Stride frequency was similar between the three different depths during walking but lower in waist-deep water during running. VO_2/stride was significantly higher ($p \leq 0.01$) in water-based walking and running compared to land-based values. Water-based walking and running elicited a greater physiological cost than land-based exercise, which can be attributed to the elevated cost of moving in water due to increased resistance. When running in waist-deep water, buoyancy may counter the resistance of the water and serve to lower the physiological cost of locomotion.

Keywords aquaciser, energy cost, buoyancy, immersion, oxygen consumption

Received 1 October 2002; accepted 10 February 2003.

The authors would like to thank the following people: Jim Grant for the use of the Aquaciser at the Royal United Hospital; Katie Buck and Jane Hall for sharing their experiences of working in this area of research and Simon Roberts for his technical assistance.

Address correspondence to Lars R. McNaughton, Department of Sport Science, University of Hull. Kingston upon Hull, HU6 7RX, United Kingdom. Email: l.mcnaughton@hull.ac.uk

Introduction

It has been well recognized that exercise in water can be an effective and useful mode of therapeutic exercise (Bishop, Frazier, Smith et al. 1989; D'Acquisto, D'Acquisto, and Renne 2001; Dowzer, Reilly, and Cable 1998; Nakazawa, Yano, and Miyashita 1994; Napoletan, Janes, and Hicks 1991). Patients suffering from injury or dysfunction of the lower extremities often experience difficulty with the weight-bearing components of land exercise. This led to the adoption of deep-water (DW) and shallow-water (SW) walking and running by many therapists, as the buoyancy provided by the water served to reduce the impact forces, and hence pain, on the lower limbs (Hall, Skevington, Maddison et al. 1996).

When an athlete has to abstain from training, decrements occur in parameters that determine aerobic fitness (Coyle, Martin, Sincamore et al. 1984). Participation in endurance exercises such as water running may help to minimize performance decrements in injured athletes (Bushman, Flynn, Andres et al. 1996; Wilber, Moffatt, Scott et al. 1996). It has also been demonstrated that water running may be beneficial in enhancing cardiovascular fitness for untrained subjects (Davidson and McNaughton 2000; Michaud, Brennan, Wilder et al. 1995; Morrow, Jensen, and Peace 1996).

The initial research in this area was conducted using DW running (Bishop, Frazier, Smith et al. 1989; Frangolias and Rhodes 1996; Gehring, Keller, and Brehm 1996; Mercer and Jensen, 1998; Svedenhag and Seger 1992), which is performed in the deep end of a swimming pool and simulates the movement pattern used for land running. It has been recognized that DW running results in altered technique when compared to running on land (Dowzer and Reilly 1998; Svedenhag and Seger 1992). This led to the introduction of SW exercise into rehabilitation and conditioning programs (Dowzer, Reilly, Cable et al. 1999; Evans, Cureton, and Purvis 1978; Town and Bradley 1991), as it more closely resembled running on land. However, SW running and walking can produce a postural distortion due to frontal resistance (Byrne, Craig, and Willmore 1996). Underwater treadmills enable subjects to walk in a more normal ambulatory posture due to diminished frontal resistance. This is especially important for patients undergoing rehabilitation in which the aim is a return to correct functional gait patterns (Hall, Macdonald, Maddison et al. 1998).

When the individual is at rest and immersed in water up to the neck, a 30%–35% increase in CO has been reported (Dowzer and Reilly 1998). This has been attributed to an increase in SV (Christie, Sheldahl, and Tristani 1990; Farhi and Linnarsson 1977) and is believed to be the result of the increased central blood volume caused by the increased pressure on the thoracic cavity and abdomen by the water (Christie, Sheldahl, and Tristani 1990). There are contrasting results between researchers as to the effect of water immersion on resting heart rate (HR). Derion, Guy, Tsukimoto et al. (1992) and Christie, Sheldahl, and Tristani (1990) found no significant difference in HR values for land and water-based conditions.

Farhi and Linnarsson (1977), on the other hand, found that water immersion between the level of the hips and the neck decreased HR by as much as eight beats per minute. They speculated that the level of immersion was associated with changes in cardiovascular parameters, reporting that SV was higher in water compared to land values and that SV increased with an increased depth of immersion. Thus it appears that walking and running in water at different depths may have important implications for cardiovascular training.

Deep-water running has been reported to elicit lower $\dot{V}O_{2max}$ and maximal HR (HR_{max}) values compared to running on a treadmill on land (Bishop, Frazier, Smith et al. 1989; Frangolias and Rhodes 1996; Michaud, Brennan, Wilder et al. 1995; Svedenhag and Seger 1992). Differences in muscle recruitment patterns and redistribution of central blood flow have been implicated in these altered responses. It is believed that confounding factors such as water temperature and the fitness of the subjects may influence HR and $\dot{V}O_2$ relationships (Buck, McNaughton, Sherman et al. 2001; Dowzer and Reilly 1998; McArdle, Magel, Lesmes et al. 1976). During maximal exercise, SW running at waist level has been illustrated to better simulate land-based running physiological responses in trained distance runners (Dowzer, Reilly, Cable et al. 1999; Town and Bradley 1991).

Few studies have been conducted to examine the effect of water immersion on submaximal exercise, and even fewer have investigated the responses on underwater treadmills. The present study compared the physiological responses of conventional land-based treadmill exercise and underwater treadmill exercise at two different depths of water. The relationship between the physiological responses of running and walking also was compared to see if the selected ambulatory mode had any influence.

Methods

Subjects

Six students—(mean ± SD) age 23.2 ± 2.9 yr, height 179.5 ± 9.9cm, and weight 66.3 ± 11.3 kg—volunteered to participate in this study. Subjects were recruited on the basis that they were recreationally active and free from any known disease or orthopaedic dysfunction. In addition, the participants were required to complete a preexercise medical screening questionnaire. Prior to data collection, the study received ethical approval from the departmental ethics committee. All aspects of the procedures, risks, and benefits of the study were explained to the participants before they provided written informed consent.

Equipment

A Powerjog JX200 treadmill (Sport Engineering Ltd) was used for land-based testing of the physiological responses of the subjects. The exercise bouts in water were performed on an AquaCiser II underwater treadmill (AquaCiser, Ferno UK Ltd), which allowed running/walking in varied depths and at different speeds. Metabolic data, including $\dot{V}O_2$ and respiratory exchange ratio (RER), were collected using a portable metabolic system (Cosmed k4b^2 SRL, Italy). Heart rate also was acquired using the k4b^2 Cosmed by attaching a Polar Vantage NV (Polar Electroy, Kempele, Finland) around the chest of the subject.

Protocol

All subjects were unfamiliar with underwater treadmill running/walking and therefore each was given a 15-minute practice session prior to the day of testing. After familiarization, all subjects completed the treadmill tests in both a land-based and a water-based environment. The participants were asked to abstain from heavy exercise 48 hours prior to any testing and to refrain from caffeine on the actual day of testing. The water-based treadmill speed was calibrated to eliminate any discrepancies with the land-based treadmill.

Subjects were required to complete six tests for running and walking in three different conditions: land, thigh-deep water, and waist-deep water. Thigh-deep was defined as the point midway between the anterior superior iliac spine and the central patella, and waist-deep was defined as the level of the umbilicus. Subjects performed a walking test for 5 minutes at 4.0km/h and a running test for 5 minutes at 7.0km/h for each environmental condition. Subjects were instructed to maintain a reciprocal arm action for running/walking in all tests. This was defined as having the elbows flexed to 90° with the forearms in the mid-prone position (Hall, Macdonald, Maddison et al. 1998).Water temperature was adjusted to 33°C prior to every water-based test.

Prior to each exercise test, the Cosmed was calibrated using gases of known concentration (O_2 16.0%, CO_2 5.0%) as well as room air. After being fitted with the Cosmed k4b^2, the subject was asked to step onto the treadmill and, in the case of water-based exercise, the required depth of water was added to the chamber. Subjects then walked or ran for 4 minutes at the required speed (to obtain steady-state exercise values (Byrne, Craig, and Willmore 1996)) before metabolic and cardiovascular measurements were collected. Oxygen uptake, HR, and RER were then collected in the fifth minute of exercise. Stride frequency (SF) was measured for 30 seconds in the fourth minute, which was then doubled.

Data Analysis

All analyses were performed using the Statistical Package for Social Sciences© (SPSS, version 8.0; Chicago, Illinois, U.S.). Submaximal values of $\dot{V}O_2$, HR, RER, SF, and $\dot{V}O_2$ per stride (the $\dot{V}O_2$ per stride was found by simply dividing the measured $\dot{V}O_2$ by the SF) were analyzed using separate two-way (ambulatory mode x level of immersion) analyses of variance with repeated measures. Statistical significance was set at $p \leq 0.05$. Where a significant main effect was observed, post-hoc pair-wise comparisons were calculated using the Bonferroni method.

Results

Oxygen Uptake

The two-way ANOVA with repeated measures revealed significant effects for ambulatory mode and depth. Values for $\dot{V}O_2$ were found to be significantly higher during running when compared to walking ($p \leq 0.001$). The highest $\dot{V}O_2$ was associated with thigh-deep exercise, which was significantly higher than waist-deep ($p \leq 0.01$) and land-based values ($p \leq 0.01$). Waist-deep $\dot{V}O_2$ was also significantly higher than the land-based trials ($p \leq 0.02$).

The relationship between the ambulatory mode and depth, although not statistically significant ($p = 0.054$), still displayed a marked interaction effect (Figure 1). It can be seen that both land and waist-deep trials respond in a similar manner to the ambulatory mode increasing by 13.80 and 13.00 ml/min/kg, respectively (Tables 1 and 2). In contrast, $\dot{V}O_2$ increased by 19.23 ml/min/kg when progressing from walking to running in thigh-deep water.

Stride Frequency

The two-way ANOVA with repeated measures revealed significant effects for ambulatory mode, depth, and interaction between the ambulatory mode and depth.

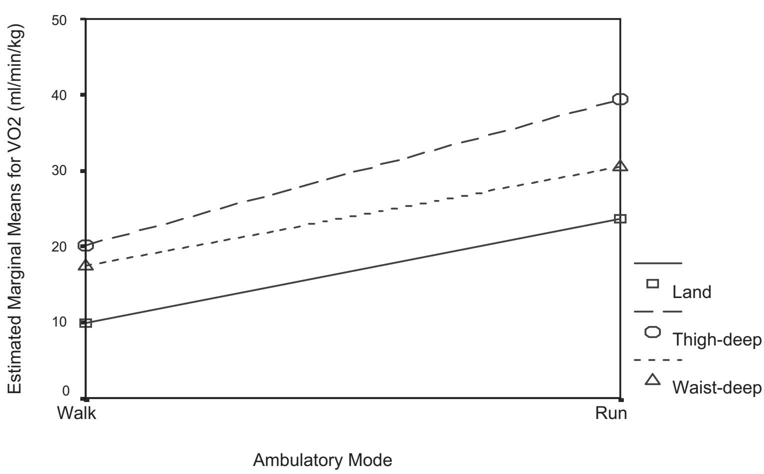

Figure 1. Interaction between the ambulatory mode and the level of immersion for oxygen uptake.

Table 1
Comparison of Physiological Variables of Interest During Walking at Three Different Depths

	Land	Thigh-deep	Waist-deep
$\dot{V}O_2$ (ml/min/kg)	9.84 ± 0.84	20.16 ± 2.32	17.48 ± 2.47
HR (beats/min)	78 ± 10	104 ± 5	96 ± 5
RER	0.85 ± 0.07	0.79 ± 0.05	0.81 ± 0.03
SF (strides/min)	101 ± 6	96 ± 7	92 ± 10
$\dot{V}O_2$/stride (ml/min/kg)	0.10 ± 0.01	0.21 ± 0.04	0.19 ± 0.04

Note: Values are expressed as the mean ± standard deviation

Table 2
Comparison of Physiological Variables of Interest During Running at Three Different Depths

	Land	Thigh-deep	Waist-deep
$\dot{V}O_2$ (ml/min/kg)	23.64 ± 0.84	39.39 ± 8.11	30.48 ± 4.54
HR (beats/min)	124 ± 7	162 ± 10	130 ± 4
RER	0.88 ± 0.06	0.85 ± 0.07	0.85 ± 0.04
SF (strides/min)	149 ± 12	143 ± 11	122 ± 12
$\dot{V}O_2$/stride (ml/min/kg)	0.16 ± 0.03	0.28 ± 0.06	0.25 ± 0.05

Note: Values are expressed as the mean ± standard deviation.

Stride frequency was higher for running compared to walking ($p \leq 0.001$) for all depths.

The ANOVA revealed that waist-deep exercise had a significantly lower SF than thigh-deep ($p \leq 0.001$) and land-based ($p \leq 0.003$) tests. The ANOVA combines walking and running values, and inspection of Figure 2 indicates that the main discrepancy in SF occurs during running. Land-based and thigh-deep trials illustrate a 48% and 49% increase in SF, respectively, between walking and running (Tables 1 and 2). The increase in SF from walking to running was only 33% in the waist-deep exercise.

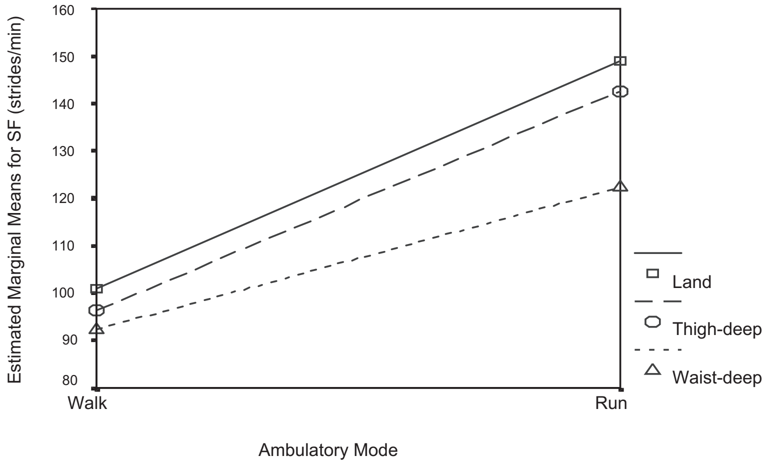

Figure 2. Interaction between the ambulatory mode and level of immersion for stride frequency.

Oxygen Cost Per Stride

Running produced an elevated $\dot{V}O_2$ per stride relative to walking ($p \leq 0.001$). Depth also appeared to have an effect. Land-based trials resulted in a significantly lower $\dot{V}O_2$ per stride in relation to both thigh-deep ($p \leq 0.01$) and waist-deep ($p \leq 0.01$) trials. There was no difference between the thigh-deep and waist-deep conditions during either walking or running.

The oxygen cost per stride was not affected by an interaction between the ambulatory mode and level of immersion (Figure 3). The increase from walking to running was similar for the three different depth treatments.

Heart Rate

Significant effects on HR were observed for ambulatory mode, depth, and the interaction between the ambulatory mode and depth. Heart rate was elevated during running compared to walking ($p \leq 0.001$) for all depths. Comparing depth responses revealed that thigh-deep exercise elicited a higher HR response than waist-deep ($p \leq 0.01$) and land-based ($p \leq 0.001$) exercise. Additionally, waist-deep HR was higher than land-based HR ($p \leq 0.04$).

During walking, HR values for waist-deep and thigh-deep water were similar, with mean values of 96 ± 5 and 104 ± 5 bpm, respectively. Land-based HR values were much lower, with a mean value of 78 ± 10 bpm (see Tables 1 and 2). Figure 4 indicates that the HR increase from walking to running is lower for the waist-

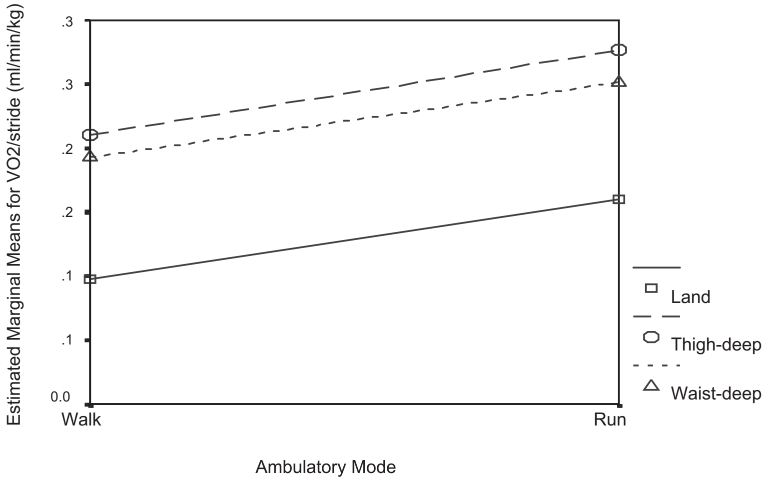

Figure 3. Interaction between the ambulatory mode and level of immersion for oxygen uptake per stride.

deep condition than thigh-deep and land-based responses. Waist-deep HR increased only 35%, compared to 56% and 58% during thigh-deep and land-based trials, respectively (Tables 1 and 2).

Respiratory Exchange Ratio

The only statistically significant effect on RER was that of the ambulatory mode. The RER was elevated during running in comparison to walking ($p \leq 0.001$). Although not significantly higher, RER was found to be highest during both walking (Table 1) and running (Table 2) on land. Thigh-deep walking and running displayed the lowest RER values.

No significant interaction was found between the ambulatory mode and depth. Figure 5, however, suggests that thigh-deep immersion produced a relatively larger increase in RER between walking and running. It should be noted that the standard deviations for land-based and thigh-deep trials were large (Tables 1 and 2).

Discussion

Oxygen Uptake

The elevated $\dot{V}O_2$ during running compared to walking was true for both water and land tests, as $\dot{V}O_2$ is proportional to the intensity of exercise. When the in-

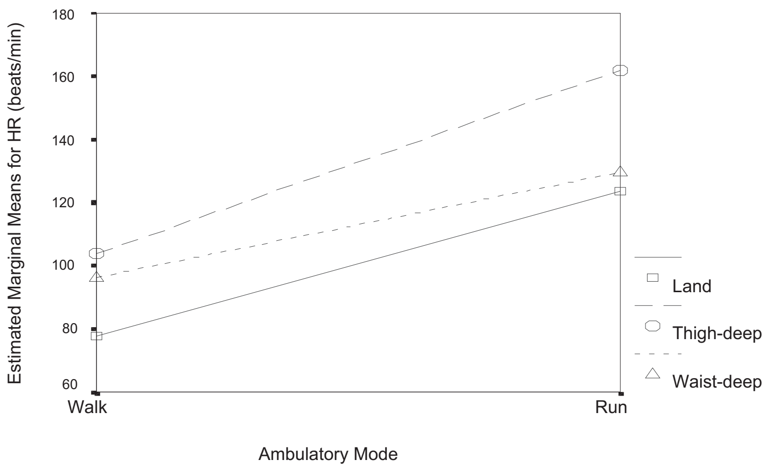

Figure 4. Interaction between the ambulatory mode and level of immersion for heart rate.

tensity of exercise is increased, the muscles involved have to perform more mechanical work, so more oxygen must be both supplied to and taken up by the muscles.

Both thigh- and waist-deep levels expressed higher values for walking and running than the respective land-based values. This could be attributed to the added resistance imposed by the water on the body during aquatic locomotion, as water is approximately 800 times more dense than air (Dowzer and Reilly 1998). Thigh-deep $\dot{V}O_2$ during running, however, also was substantially higher than that of waist-deep running, which is in keeping with the findings of Gleim and Nicholas (1989). They postulate that the most likely explanation is that the flight phase during running is prolonged due to the buoyancy of the human body, which would allow the subject to float momentarily while the belt runs underneath, thus reducing the workload. During thigh-deep running, it could be postulated that not enough of the body is immersed to benefit from the lift forces provided by buoyancy. Napoletan and Hicks (1995) found that chest-deep running produced a $\dot{V}O_2$ that was 13.6 ml/min/kg lower than thigh-deep running at a speed of only 5.5 km/h. This is a much larger difference in $\dot{V}O_2$ than was found between the thigh- and waist-deep values in this study. This could be due to buoyancy being increased further at chest level, serving to decrease the metabolic cost even more.

The enhanced buoyancy would not be of as much significance during walking, as the ambulatory mode lacks a flight phase, so the subject must match the speed of the belt more precisely. This is evidenced in the results, as $\dot{V}O_2$ for thigh-deep walking is only 2.68 ml/min/kg higher than waist-deep values. Once again,

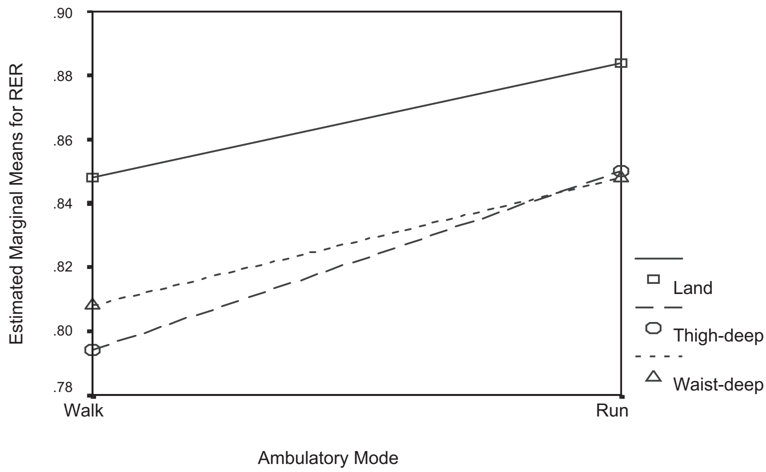

Figure 5. Interaction between the ambulatory mode and level of immersion for RER.

this is similar to the study conducted by Gleim and Nicholas (1989), in which thigh-deep walking was 2.3 ml/min/kg higher than waist depth. If buoyancy was not acting during walking, it might be expected that $\dot{V}O_2$ would be higher during the waist-deep condition because a greater proportion of the body is immersed and must overcome the greater resistance of the water. It would, therefore, be incorrect to state that buoyancy is not a factor during walking. The lowered metabolic responses at waist depth found during running are simply due to the increased influence of buoyancy.

Stride Frequency

A significant finding of this study was that the waist-deep condition resulted in a lower SF than both the thigh-depth and land-based conditions. The ANOVA, however, combined the walking and running values for the depth conditions and then compared them. Closer inspection of the interaction revealed that SF for the waist-deep condition was significantly influenced by the ambulatory mode. When subjects are walking, SF is similar for land-based, thigh-deep, and waist-deep conditions. During running, however, although the land-based and thigh-deep SF remain similar, the SF for the waist-deep condition is more than 20 strides/min lower. Thus, it appears that the difference for the waist-deep condition can be attributed mainly to the discrepancy of SF during running.

The findings of this study are in contrast to those of Hall, Macdonald, Maddison et al. (1998), who discovered a significant difference in SF between water- and land-based walking. The authors found that at all walking speeds, SF in water was 27 strides/min lower than on land. A possible explanation for the contrasting findings is that the study by Hall, Macdonald, Maddison et al. (1998) immersed the subjects to the level of the xiphoid. It has been postulated previously that an increased level of water immersion may serve to enhance the lift forces due to buoyancy. In turn, this might increase the duration of the gait cycle.

The buoyancy theory also would be of use in explaining the discrepancy found for SF during waist-deep running. It could be argued that the decreased SF was due to a prolonged flight phase in the gait cycle, which would serve to increase the time to perform one stride. Thigh-deep SF during running has to match the land-based value, because little buoyancy is provided by the water at this depth. Thus, the lower SF found during waist-deep running provides additional evidence that the lowered metabolic cost for this condition may be due to buoyancy.

Stride frequency alone, however, cannot be used to explain the lowered $\dot{V}O_2$ cost during waist-deep running. It could be plausible that the decreased SF was, in fact, due to the higher resistance of the water acting on a greater proportion of the body. The lowered $\dot{V}O_2$ response could be explained by decreased work required between the body and the ground during the support phase of gait. In order to determine which factor is more important, the $\dot{V}O_2$ cost per stride also needs to be taken into account.

Oxygen Cost Per Stride

The oxygen cost per stride appears to be lower in land-based walking and running compared to the respective values at both different water depths. This elevated cost can be attributed to water viscosity and the increased resistance to locomotion. Hall, Macdonald, Maddison et al. (1998) reported $\dot{V}O_2$ costs per stride of 6.73 and 10.48 ml/min for land and water walking (4.5km/h), respectively. If the results from the present study are converted to similar units, comparative values of 6.5 and 12.9 ml/min are displayed for land and water. The lower value for water walking found by Hall, Macdonald, Maddison et al. (1998) could be due to the deeper level of water immersion. The resulting increase in buoyancy would lower the work required during the support phases of the gait cycle.

If the increasing water immersion did serve to decrease the work intensity, it would be expected that the $\dot{V}O_2$ per stride would be lower in waist-deep water exercise compared to thigh-deep exercise. The results indicate that this is not the case, and that the two water depths illustrate similar costs for both walking and running. The explanation may lie in the interaction between water resistance and buoyancy. As the level of immersion increases from thigh depth to waist depth, the effects of buoyancy would become more pronounced. At the same time, the increased depth also would mean that a greater proportion of the body would have to overcome the resistance of the water. Therefore, the work-reducing effect of the buoyancy may be countered by the increased water resistance.

A similar $\dot{V}O_2$ cost per stride is found for both thigh-deep and waist-deep running in water. This seems to imply that the $\dot{V}O_2$ cost per stride cannot explain the lowered $\dot{V}O_2$ response in waist-deep running compared to thigh-deep values. Thus, it appears that the lowered metabolic response during waist-deep running is simply due to the fact that subjects take fewer strides.

Heart Rate

When the subjects walked, HR was considerably higher in the water conditions when compared to the land-based HR value (78 beats/min). Walking in thigh-deep water (104 beats/min) elicited a slightly higher HR than waist-deep water (96 beats/min), which was exactly the case with $\dot{V}O_2$. It could be suggested that the HR for all three conditions simply represented the metabolic cost of the walking. The results of this study are comparable with those of Gleim and Nicholas (1989), who found HR values of 81, 105, and 98 beats/min for land-based, thigh-deep, and waist-deep conditions, respectively. It appears that while walking at different levels of water immersion, HR is simply a function of exercise intensity and metabolic cost.

Thigh-deep running elicited the highest HR response during running, followed by waist-deep and then land-based conditions. The significant interaction between depth and ambulatory mode, however, implies that HR trends are different during running and walking. The main point is that HR for waist-deep water running has increased only 35% from the value recorded during walking, which is low compared with the 56% and 58% increases found in the thigh-deep and land-based tests.

There is no clear explanation for this dampened HR response, but one theory is that the phenomenon is a result of an interaction between the baroreceptor and Bainbridge reflexes. If the level of immersion is sufficient to increase the hydrostatic pressure on the thoracic cavity, a redistribution of blood centrally can be expected. Thus, the resulting increase in stroke volume would prompt a decrease in HR via the baroreceptor reflex. It is possible that during low-moderate intensity exercise the increased atrial pressure acts to offset the bradycardia. Another possible explanation is that water immersion may affect the autonomic nervous system (Christie, Sheldahl, and Tristani 1990). During exercise, HR is controlled by both divisions of the autonomic nervous system and is elevated by simultaneously increasing sympathetic and decreasing sympathetic activity. The initial increase in heart rate (up to 100 beats/min) during exercise is due to parasympathetic neural withdrawal, whereas sympathetic neural outflow should have a greater impact on HR at higher work rates (Powers and Howley 2001). This would imply that HR while walking in waist-deep water was mainly controlled by parasympathetic withdrawal, but running was controlled by sympathetic stimulation. It has been suggested that sympathetic neural outflow is reduced in water (Christie, Sheldahl, and Tristani 1990), which would imply that HR during running might be lower than expected. The values of HR for walking are less affected because this condition would rely less on sympathetic stimulation. The increase in HR between walking and running in thigh-deep water was not depressed, which may imply that the level of immersion was not sufficient to cause a decreased sympathetic response.

Respiratory Exchange Ratio

The only clear effect on RER was that it was significantly elevated during running in comparison to walking. This effect was evident irrespective of the level of water immersion. This can be explained by the fact that low-intensity exercise relies primarily on fat as fuel, but as the intensity increases, muscles increasingly rely on carbohydrate sources of energy.

During walking and running, the land-based condition demonstrates the highest values of RER, but also the lowest $\dot{V}O_2$ and HR values. This implies that despite a higher exercise intensity required to move in water, RER is lower than land responses. It would be expected, however, that the increased cost of moving in water would result in a higher RER. This was illustrated by Hall, Macdonald, Maddison et al. (1998), who demonstrated RER values of 0.94 and 0.89 when walking in water and land, respectively. This could be due to calculations of RER, assuming that the body's CO_2 exchange in the lung is proportional to its release from the cells. Body CO_2 pools are quite large, however, and can be altered by breathing patterns. Under these conditions, the CO_2 released in the lung may not actually represent that being produced in the tissues. This would bias the ratio of VCO_2 to $\dot{V}O_2$ and invalidate the use of RER to estimate fuel utilization. Another likely explanation for the confounding RER values is the large standard deviation values associated with the means. No significant differences were found between land-based, thigh-deep, and waist-deep conditions.

Application of Findings

Despite the assumed reduced impact forces during water exercise, running in thigh-deep and waist-deep water still seems to induce a physiological response that could stimulate a training response. A subject who is utilizing water running for rehabilitation purposes probably would begin a program using a relatively high water depth in order to take full advantage of the reduced impact forces. Because the vertical ground reaction forces increase as the level of immersion in reduced (Nakazawa, Yano, and Miyashita 1994), it might be expected that as the injury improves a progressively lower immersion level would be used to increase loading on the injured joint. The implications of this study are that as the level of immersion is decreased, the workload must be adjusted accordingly, as exercise is more intense in more shallow water.

Additionally, water running can be used by injury-free subjects as a training tool, as the reduced impact may decrease the susceptibility of the lower extremities to injury and could be used in conjunction with on-land training. To enable the subject to train at a similar intensity to land-based running, the relationship between water and land running must be known. The present study, however, used only one speed to represent walking and running. This may be inaccurate, as the variation of speed within the ambulatory mode might also influence physiological responses. This was highlighted by Gleim and Nicholas (1989), who found that at higher running speeds (> 8 km/h) waist-deep $\dot{V}O_2$ was similar to land-based values. Further investigation is required into the interaction of depth and ambulatory mode at more speeds.

Because the mechanism for the lowered HR response during waist-deep running is currently unclear, further investigation into cardiovascular responses to water immersion per se is needed. The contribution of baroreceptor and Bainbridge responses must be determined as a function of both exercise intensity and immersion per se. Additionally, the effect of water immersion on the sympathetic nervous system needs investigation. The level of immersion required to influence this mechanism also needs to be established.

Finally, the justification for this study was provided by the theory that water exercise provided a cardiovascular workout without the high-impact forces present in land exercise. Some subjects, however, commented that they felt greater pressure on the joints (especially the knee) during water walking and running. It should be noted that although Nakazawa, Yano, and Miyashita (1994) demonstrated decreasing vertical ground reaction forces with increasing water immersion, this does not guarantee decreased internal joint forces in the lower extremity. The increased resistance of water is an additional external force acting on the lower extremity joints during water walking and running. Biomechanical investigation into the kinetics of the gait cycle in water also is an important avenue for future work.

References

Bishop PA, Frazier S, Smith J, Jacobs, D (1989) Physiological responses to treadmill and water running. *The Physician and Sportsmedicine* 17:87–94.

Buck K, McNaughton L, Sherman R, Bentley DJ, Batterham AM (2001) Physiological response to treadmill walking in water at different speeds and temperatures. *Sports Medicine Training and Rehabilitation* 10:105–122.

Bushman BA, Flynn MG, Andres FF, Lambert CP, Taylor MS, Braun WA (1996) Effect of 4 wk of deep water run training on running performance. *Medicine and Science in Sports and Exercise* 29:694–699.

Byrne HK, Craig JN, Willmore JH (1996) A comparison of the effects of underwater treadmill walking to dry land treadmill walking on oxygen consumption, heart rate, and cardiac output. *The Journal of Aquatic Physical Therapy* 4:4–11.

Christie JL, Sheldahl LM, Tristani FE (1990) Cardiovascular regulation during head-out water immersion. *Journal of Applied Physiology* 69:657–664.

Coyle EF, Martin DR, Sincamore DR, Joyner MJ, Hagverg JM, Holloszy JO (1984) Time course of loss of adaptation after stopping prolonged intense endurance training. *Journal of Applied Physiology* 57:1857–1864.

D'Acquisto LJ, D'Acquisto DM, Renne D (2001) Metabolic and cardiovascular responses in older women during shallow-water exercise. *Journal of Strength and Conditioning Research* 15:12–19.
Davidson K, McNaughton L (2000) Deep water running training and road running training improve Vo(2)max in untrained women. *Journal of Strength and Conditioning Research* 14:191–195.
Derion T, Guy HJB, Tsukimoto K, Schaffartzik W, Prediletto R, Poole DC, Knight DR, Wagner PD (1992) Ventilation-perfusion relationships in the lung during head-out water immersion. *Journal of Applied Physiology* 72:64–72.
Dowzer CN, Reilly T (1998) Deep-water running. *Sports Exercise and Training* 4:56–61.
Dowzer CN, Reilly T, Cable NT (1998) Effects of deep and shallow water running on spinal shrinkage. *British Journal of Sports Medicine* 32:44–48.
Dowzer CN, Reilly T, Cable NT, Nevill A (1999) Maximal physiological responses to deep and shallow water running. *Ergonomics* 42:275–281.
Evans BW, Cureton KJ, Purvis JW (1978) Metabolic and circulatory responses to walking and jogging in water. *Research Quarterly for Exercise and Sport* 49:442–449.
Farhi LE, Linnarsson D (1977) Cardiopulmonary readjustments during graded immersion in water at 35°C. *Respiration Physiology* 30:35–50.
Frangolias DD, Rhodes EC (1996) Metabolic responses and mechanisms during water immersion running and exercise. *Sports Medicine* 22:38–53.
Gehring MM, Keller BA, Brehm BA (1997). Water running with and without a flotation vest in competitive and recreational runners. *Medicine and Science in Sports and Exercise* 29:1374–1378.
Gleim GW, Nicholas JA (1989) Metabolic costs and heart rate responses to treadmill walking in water at different depths and temperatures. *The American Journal of Sports Medicine* 17:248–252.
Hall J, Macdonald IA, Maddison PJ, O'Hare JP (1998) Cardiorespiratory responses to underwater treadmill walking in healthy females. *European Journal of Applied Physiology* 77:278-284.
Hall J, Skevington SM, Maddison PJ, Chapman K (1996) A randomized and controlled trial of hydrotherapy in rheumatoid arthritis. *Arthritis Care Research* 9:206–215.
McArdle WD, Magel JR, Lesmes GR, Pechar GS (1976) Metabolic and cardiovascular adjustment to work in air and water at 18, 25, and 33°C. *Journal of Applied Physiology* 40:85–90.
Mercer JA, Jensen RL (1998) Heart rates at equivalent submaximal levels of VO_2 do not differ between deep-water running and treadmill running. *Journal of Strength and Conditioning Research* 12:161–165.
Michaud TJ, Brennan DK, Wilder RP, Sherman NW (1995) Aquarunning and gains in cardiorespiratory fitness. *Journal of Strength and Conditioning Research* 9: 78–84.
Morrow MJ, Jensen RL, Peace CR (1996) Physiological adaptations to deep water and land based running training programmmes. *Medicine and Science in Sports and Exercise* 28:S210.
Nakazawa K, Yano H, Miyashita M (1994) Ground reaction forces during walking in water. *Medicine and Science in Aquatic Sports* 39:28–34.
Napoletan J, Janes J, Hicks R (1991) The effect of underwater treadmill exercise in the rehabilitation of ACL reconstruction. *Medicine and Science in Sports and Exercise* 5: S32.

Napoletan JC, Hicks RW (1995) The metabolic effects of underwater treadmill exercise at two depths. *American Physical Therapy Research* 3:9–13.

Powers SK, Howley ET (2001) *Exercise Physiology* (4th Edition). New York: McGraw-Hill. p166–168, 173–174.

Svedenhag J, Seger J (1992) Running on land and in water: comparative exercise physiology. *Medicine and Science in Sports and Exercise* 24:1155–1160.

Town GP, Bradley SS (1991) Maximal metabolic responses of deep and shallow water running in trained runners. *Medicine and Science in Sports and Exercise* 23:238–241.

Wilber RL, Moffatt RJ, Scott BE, Lee DT, Cucuzzo NA (1996) Influence of water run training on the maintenance of aerobic performance. *Medicine and Science in Sports and Exercise* 28:1056–1062.