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A comparison of muscle activity and heart rate response during backward and forward walking on an underwater treadmill

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Abstract

This investigation compared muscle activities and heart rate (HR) responses while subjects walked backward or forward in water, with and without a water current. Ten healthy males (23.5 ± 1.4 years) volunteered for the study. Surface electromyography (EMG) was used to evaluate muscle activities while the subjects walked in water, immersed to the level of the xiphoid process. HR responses were monitored continuously by a telemetry method. A ‘‘Flowmill’’ was used for this study, which involves a treadmill at the base of a water flume. Measurement of maximal voluntary contraction (MVC) of each tested muscle was undertaken prior to gait analysis. The %MVCs obtained from the paraspinal muscles, vastus medialis and tibialis anterior were all significantly greater when walking backward than when walking forward, for every experimental condition ($P < 0.05$). HR responses tended to be greater while walking backward than when walking forward, with a statistical significance at fast speed ($P < 0.05$). In conclusion, walking backward in water resulted in significantly greater muscle activation of the paraspinal muscles, vastus medialis and tibialis anterior compared with walking forward in water. These findings may be helpful in developing water-based exercise programs.

Keywords: EMG; HR; Backward; Water; Gait

1. Introduction

Water-based exercise programs have become popular for both fitness enhancement and rehabilitation [1]. Walking and jogging in water have been used as part of rehabilitative, therapeutic, and general conditioning programs [2]. Numerous studies have documented the psychological [3], metabolic [2], cardio respiratory [4], thermoregulatory [5], and physiological [1,6] responses to various forms of water-based exercise, but there are no well-designed scientific investigations describing muscle activities, or the influence of a water current on muscle activities while subjects walk in water. Recently, Masumoto et al. [7] successfully employed surface electrode and telemetric electromyography (EMG) technology to analyze muscle activities in healthy young subjects while walking in water. They demonstrated decreased muscle activity in water (~70% MVC of that observed on dry land), but this activity increased in the presence of a water current [7].

Walking backward has been used for rehabilitation following lower extremity injuries and for injury prevention [8]. It elicits an increased neuromuscular demand, when compared to walking forward. The EMG activity for the rectus femoris and vastus medialis has been found to be considerably higher when walking backward rather than forward on dry land [9]. Furthermore, running backward requires a longer period of quadriceps activity and can result in greater quadriceps strength gain than that achieved by running forward on dry land [9,10]. On the other hand,

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walking backward on dry land reduces the compressive forces at the patellofemoral joint and decreases force absorption of the knee, due to reduced eccentric function of the quadriceps muscle [11]. Although the eccentric function of quadriceps strength is reduced while walking backward on dry land, it has been found that isometric and concentric quadriceps strength can be maintained [10]. Additional benefits of walking backward include increased cardiopulmonary demand, since backward locomotion, both walking and running, has been shown to produce higher cardiopulmonary demand than forward locomotion [8,12,13]. Several investigators have suggested that backward locomotion increases oxygen uptake ($\dot{V}_{O_2}$) by 17–78%, compared with forward locomotion [8,12,14,15]. Furthermore, walking backward on dry land has also been shown to increase energy expenditure to a level high enough for cardiorespiratory fitness to be maintained [12,13]. However, there is no quantitative evidence available which compares the specific biomechanical responses that occur during walking forward or backward in water. Clear scientific evidence of the fundamental neuromuscular function and the hydrodynamic properties of water in the case of healthy individuals would help to provide a framework for planning a progressive water-based exercise program, which should be safely applied for rehabilitative or recreational purposes.

Previous studies have estimated physiological responses while walking in a swimming pool [2,6]. However, it has been methodologically difficult to identify the physiological intensity involved. The present study utilized a newly developed underwater treadmill known as the ‘‘Flowmill’’ which involves a treadmill at the base of a water flume. Its major advantage is that the water temperature, depth, walking speed, and water current can each be controlled individually, and thus the functional walking patterns and exercise intensity can be adjusted.

The present study represents the first attempt to compare muscle activities and heart rate (HR) responses in healthy subjects while walking backward or forward in water, with and without a water current, under three different speed conditions, with a view to obtaining basic data for help in planning optimal exercise prescriptions. Based on previous findings, we hypothesized that both muscle activity [9,16] and HR [8,12] would be greater during backward walking in water, compared to forward walking in water.

2. Methods

2.1. Subjects

A total of 10 healthy male individuals (age, 23.5 ± 1.4 years; height, 176.6 ± 4.4 cm; body mass, 72.6 ± 11.1 kg; and %fat, 20.6 ± 5.2%; mean ± S.D., respectively) participated in the study. Percentage fat was estimated using the impedance method (TBF-410, Toyo Physical, Japan). All subjects were free from pain, injury, or any known chronic or acute diseases at the time of the study. The subjects had not been participating in any exercise regularly at the time of data collection. This study was approved by the Ethical Committee of the Department of Rehabilitation Medicine at Kyushu University Hospital. Informed consent to participate in the study was obtained by all subjects.

2.2. Electromyograms

The gait analysis protocol followed the previously described methods of Masumoto et al. [7]. EMGs of each muscle were obtained using 8 mm silver–silver chloride surface electrodes (Mini Ag/AgCl Skin Electrode, NT-511G, Nihon Kohden, Japan), in order to evaluate muscle activities. In order to keep the inter-electrode resistance low (<5 kΩ), the sites for electrode placement were prepared by shaving the hair and gently abrading the skin using a skin preparation gel (Skinpure, YZ-0019, Nihon Kohden). These sites were cleaned with alcohol pads in order to minimize the skin resistance. EMG signals were captured from the following muscles on the right side: the gluteus medius, vastus medialis, the long head of the biceps femoris, tibialis anterior, the lateral head of the gastrocnemius, rectus abdominis, and paraspinal muscles at the level of L4. A reference electrode was placed on the acromion. In order to minimize cross-talk between muscle groups, surface electrodes were placed 2 cm apart over the middle point of the muscle belly. Waterproof dressings were placed over each of the electrodes. The surface electrodes were fixed with extreme care using adhesive tape (3 M, USA) before being covered with foam pads (Foam Pad, 75A, Nihon Kohden) in order to prevent water from contacting the skin-electrode interface and to prevent electrical leakage during the tests. Taping was undertaken in a manner that allowed unencumbered movement of the tested muscles and normal gait while performing the trials. These procedures were carried out by one particular investigator in order to ensure identical standard record keeping.

The raw EMG signal was derived with the eight-channel multitelemeter system (WEB-5000, Nihon Kohden) and was transferred to an analogue/digital converter (MacLab/8c, AD Instruments, USA) before being imported into a personal computer (Macintosh PowerBook, 3400c, Apple Computer, USA) for later analysis. The raw EMG signal was recorded at the sampling rate of 1000 Hz and then integrated EMG (iEMG) analysis was undertaken using Chart v3.5/s (AD Instruments) and Scope v3.5/s software (AD Instruments). The EMG data were integrated after smoothing. The raw EMG signal was digitally filtered using second-order low-pass and high-pass filters with cut-off frequencies of 500 Hz and 20 Hz, respectively.

Maximal voluntary contraction (MVC) was used to normalize the EMG magnitude. Measurement of the MVC of each muscle, following the method of Hislop and Montgomery [17], was undertaken on dry land before performing gait analysis, in order to calculate the percentage of MVC (%MVC). The entire EMG activity for each muscle was expressed as a %MVC. The subjects performed a single MVC isometric contraction test for each of the tested muscles. The duration of the test was set at 5 s for each muscle. The subjects familiarized themselves with the testing procedure and were trained to produce the maximal force output before each measurement session.

EMG activities recorded for five randomly selected consecutive gait cycles were subjected to full-wave rectification. The gait cycle was determined by event markers. This method was used because no equipment (e.g., foot-switch) is commercially available for determining gait cycles during walking in water. For each subject and each muscle, the iEMGs (mV/s) of the five randomly selected consecutive gait cycles were divided by the time required for each of the gait cycles in order to calculate the iEMGs per second (mV). Then, the iEMGs were averaged in order to yield iEMGs per gait cycle. The peak 1-s EMG signal (mV) for each of the seven muscles tested during MVC measurements was selected as a normalizing value (100%). In order to calculate the %MVC, each of the iEMGs per second (mV) was divided by the peak amplitude of MVC per second (mV) for standardization.

2.3. Experimental procedures

Each subject completed all the tests within a single day. Initially, subjects completed the MVC measurement on dry land. Verbal encouragement was provided to motivate all subjects into achieving their maximal contraction levels. Then, they were required to enter the water flume. Before initiating the actual trials in water, a few submaximal EMG recordings were repeated to test accurate electrode placement, to ensure that the electrodes had not migrated and that dampening of the signal due to water leakage had not occurred. The multitelemeter system was secured to the side of the underwater treadmill during the trials, enabling the transmitter to be secured without placing undue tension on the leads or interfering with the gait.

Trials consisted of walking backward and walking forward in water, with and without a water current, on an underwater treadmill (Flowmill, FM-1200D, Japan Aqua Tech, Japan), immersed to the level of the xiphoid process. Throughout the experiment, the water temperature of the Flowmill (Fig. 1) was maintained at 31.0 ± 0.1 °C [2], a level assumed to be thermoneutral for exercising humans [18]. Room temperature was maintained at 26.6 ± 0.1 °C [7].

Before commencing the tests, all subjects practiced walking backward in water at various speeds until confident enough to proceed with the actual measurements. Additional practice was allowed if the subject or investigators considered it necessary. Each subject then completed three consecutive 1-min exercise bouts for each of the four different modes of exercise, with a 1-min rest between each of the three speed settings (1.8 km/h, 2.4 km/h and 3.0 km/h, representing slow, moderate and fast speeds). The speeds of the water current were also set at 1.8 km/h, 2.4 km/h and 3.0 km/h, in line with the speeds of the underwater treadmill. The subjects wore swimsuits throughout the sessions, and none of them had engaged in walking in water regularly, prior to the experiment. A randomized testing order was used to minimize threats to the study's internal validity.

Fig. 1. Side view of the underwater treadmill (Flowmill).

For all tests, HR responses were monitored continuously by a telemetry method (ST-30, DS-501, Fukuda-Denshi, Japan) and were recorded every 10 s, in order to estimate exercise intensity: the value at the midpoint of each exercise bout (30 s) was used for statistical analysis [7]. Waterproof electrodes (Vitrode, D-90, Nihon Koden) were used to estimate HR responses while performing the tests [7].

2.4. Statistical analysis

Data are presented as means ± S.D. All parameters were analyzed by repeated measures ANOVA (factors: walking speeds, walking directions, and water current conditions), with the Bonferroni correction for *post hoc* comparison tests. The level of statistical significance for all tests was declared at $P < 0.05$.

3. Results

3.1. Heart rate response

Descriptive statistics for HR responses in each experimental condition are presented in Table 1. HR responses

Table 1
Heart rate responses while walking forward and backward in water (with and without a water current)

Speed	Water + Cur (beats/min)		Water − Cur (beats/min)	
	Forward	Backward	Forward	Backward
Slow	77.7 ± 6.0	82.7 ± 6.9	73.9 ± 8.4	77.4 ± 6.9
Moderate	86.7 ± 6.4	90.3 ± 5.0	82.3 ± 6.3	85.9 ± 4.2
Fast	94.9 ± 7.0	96.9 ± 7.9*	87.8 ± 5.6	93.2 ± 9.7

Values are means ± S.D. Water + Cur: walking in water with a current; Water − Cur: walking in water without a current.
* $P < 0.05$ backward walking vs. forward walking.

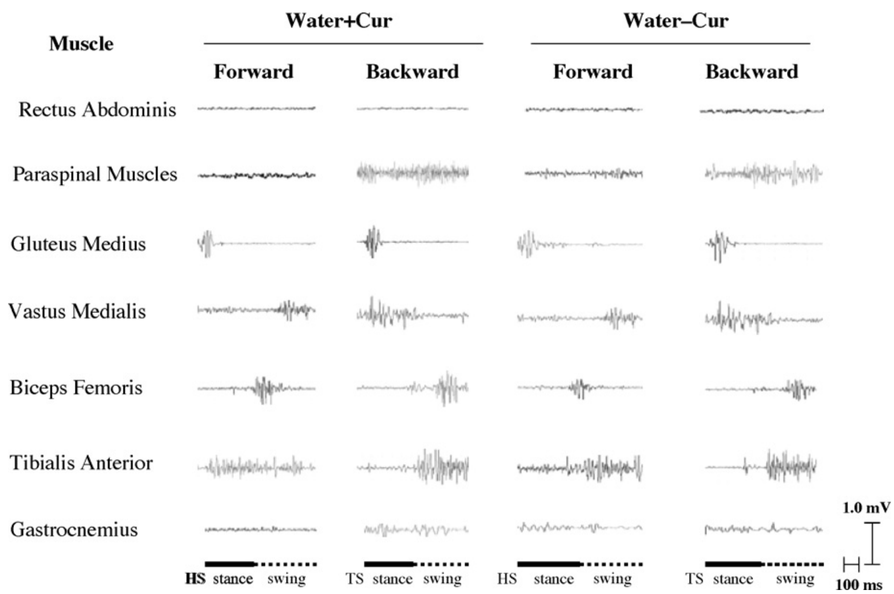

Fig. 2. Typical EMG data per gait cycle of a subject performing trials at a moderate speed. HS: heel strike; TS: toe strike; Water + Cur: walking in water with a current; Water − Cur: walking in water without a current.

tended to be greater while walking backward than when walking forward. This reached statistical significance at fast speed with a water current ($P < 0.05$). In addition, HR responses increased as speed increased ($P < 0.05$).

3.2. %MVC

Fig. 2 represents the typical raw EMG data from the tested muscles while performing the trials at moderate speed. The raw EMG activities from the paraspinal muscles, vastus medialis, and tibialis anterior increased during walking backward (both with and without a current), compared to those observed while walking forward.

The %MVCs from each of the tested muscles are presented in Tables 2 (slow speed), 3 (moderate speed), and 4 (fast speed).

At slow speed, both with and without a water current, the %MVCs from the paraspinal muscles ($P < 0.01$), vastus medialis ($P < 0.05$), and tibialis anterior ($P < 0.01$) were significantly greater when walking backward than when walking forward.

At moderate speed with a water current, the %MVCs from the rectus abdominis ($P < 0.01$), paraspinal muscles ($P < 0.01$), vastus medialis ($P < 0.01$), and tibialis anterior ($P < 0.01$) were significantly greater when walking backward than when walking forward. At moderate speed without a water current, the %MVCs from the paraspinal muscles ($P < 0.01$), vastus medialis ($P < 0.01$), tibialis anterior ($P < 0.01$), and gastrocnemius ($P < 0.05$) were also significantly greater when walking backward than when walking forward.

At fast speed with a water current, the %MVCs from the tested muscles were significantly greater when walking backward than when walking forward ($P < 0.05$), although in the case of the gastrocnemius, the difference was not statistically significant. At fast speed without a water current, the %MVCs from the paraspinal muscles ($P < 0.001$), vastus medialis ($P < 0.01$), and tibialis anterior

Table 2
The %MVCs while walking backward and forward in water (with and without a water current) at slow speed

Muscle	Water + Cur		Water − Cur	
	Forward	Backward	Forward	Backward
Rectus abdominis	4.0 ± 1.7	5.0 ± 2.2	3.5 ± 1.4	3.9 ± 1.5
Paraspinal muscles	9.1 ± 6.8	$14.4 \pm 7.5^{**}$	7.4 ± 5.5	$12.6 \pm 7.7^{**}$
Gluteus medius	8.0 ± 3.8	10.0 ± 5.3	5.9 ± 2.3	7.6 ± 3.8
Vastus medialis	4.6 ± 3.1	$9.1 \pm 3.4^{*}$	3.5 ± 2.2	$8.0 \pm 2.9^{*}$
Biceps femoris	6.0 ± 2.3	7.1 ± 1.9	4.1 ± 1.8	5.4 ± 2.5
Tibialis anterior	7.5 ± 3.4	$12.3 \pm 5.1^{**}$	7.3 ± 3.0	$12.1 \pm 4.5^{**}$
Gastrocnemius	6.0 ± 3.5	8.5 ± 4.1	6.4 ± 2.8	7.6 ± 3.3

Values are mean ± S.D. Water + Cur: water with a current; Water − Cur: water without a current.
* $P < 0.05$ backward walking vs. forward walking.
** $P < 0.01$ backward walking vs. forward walking.

Table 3
The %MVCs while walking backward and forward in water (with and without a water current) at moderate speed

Muscle	Water + Cur		Water − Cur	
	Forward	Backward	Forward	Backward
Rectus abdominis	4.3 ± 1.6	7.4 ± 4.3**	4.3 ± 2.3	6.4 ± 4.1
Paraspinal muscles	11.7 ± 9.0	17.9 ± 10.7**	9.0 ± 6.8	15.2 ± 10.5**
Gluteus medius	10.4 ± 6.8	11.7 ± 5.6	7.6 ± 2.8	9.6 ± 5.4
Vastus medialis	7.9 ± 4.5	13.6 ± 5.0**	6.1 ± 3.9	11.5 ± 4.5**
Biceps femoris	12.0 ± 9.9	12.6 ± 5.3	6.7 ± 3.2	8.1 ± 2.0
Tibialis anterior	11.1 ± 4.3	15.8 ± 4.3**	10.8 ± 4.0	15.6 ± 5.9**
Gastrocnemius	9.8 ± 4.1	11.5 ± 5.5	8.0 ± 3.9	12.2 ± 9.7*

Values are mean ± S.D. Water + Cur: water with a current; Water − Cur: water without a current.
* $P < 0.05$ backward walking vs. forward walking.
** $P < 0.01$ backward walking vs. forward walking.

Table 4
The %MVCs while walking backward and forward in water (with and without a water current) at fast speed

Muscle	Water + Cur		Water − Cur	
	Forward	Backward	Forward	Backward
Rectus abdominis	5.0 ± 2.1	11.0 ± 6.7***	5.1 ± 1.7	6.3 ± 1.8
Paraspinal muscles	15.4 ± 10.5	22.4 ± 13.7***	10.4 ± 8.2	17.7 ± 8.0***
Gluteus medius	12.8 ± 7.1	16.4 ± 7.3*	8.8 ± 4.1	10.6 ± 4.8
Vastus medialis	13.8 ± 8.9	19.3 ± 7.0**	8.7 ± 4.1	14.7 ± 5.8**
Biceps femoris	20.1 ± 8.8	24.7 ± 8.0*	14.8 ± 6.5	17.5 ± 6.3
Tibialis anterior	16.0 ± 6.4	21.0 ± 7.0**	15.1 ± 6.3	20.3 ± 9.6**
Gastrocnemius	15.9 ± 6.5	18.9 ± 8.7	11.8 ± 5.0	13.1 ± 4.8

Values are mean ± S.D. Water + Cur: water with a current; Water − Cur: water without a current.
* $P < 0.05$ backward walking vs. forward walking.
** $P < 0.01$ backward walking vs. forward walking.
*** $P < 0.001$ backward walking vs. forward walking.

($P < 0.01$) were significantly greater when walking backward than when walking forward. In addition, the %MVCs from the tested muscles were greater for faster speed ($P < 0.05$).

4. Discussion

The most important new finding of the present study was that the subjects showed significantly greater muscle activities from the paraspinal muscles, vastus medialis and tibialis anterior while walking backward in water, than when walking forward in water, for every experimental condition. Both water and air temperatures were kept within the range of thermoneutral [7,18]. In the case of the present study, it therefore follows that immersion-related changes in electromechanical factors that affect the measurement techniques or detected signal can also be assumed to be negligible.

Takeshima et al. [19] suggested that water-based exercise training studies should pay attention to the use of back muscles. Cole et al. [20] speculated that walking backward in water provides a greater emphasis on isometric paraspinal muscle conditioning, whilst also incrementally enhancing resistive exercise and the duration of activity for the muscle groups. Emphasis should be placed on the fact that significantly greater muscle activities from the paraspinal muscles were observed while walking backward in water than when walking forward, in each of the experimental conditions. This probably reflects the greater resistance of movement encountered in water, leading subjects to a greater effort in order to maintain their accurate walking position and balance. The present findings, therefore, provide scientific evidence, which supports the above speculation of Cole et al. [20].

When walking backward, the knee extensor musculature plays a major role in generating the force necessary for propulsion [21]. In fact, EMG activity for the rectus femoris and vastus medialis was considerably higher while walking backward [16]. In addition, running backward has been shown to require a longer period of quadriceps activity [9]. The present study demonstrated increased EMG activity for the vastus medialis while walking backward in water compared to walking forward, in each of the experimental conditions. This supports the above-mentioned findings on dry land [16].

The present study showed significantly greater muscle activation from the tibialis anterior while walking backward in water compared to walking forward, in each of the experimental conditions. Increased dorsiflexion of the ankle joint occurs while walking backward [22]. It can perhaps be assumed that increased muscle activation of the tibialis anterior results in greater demand for increased ankle dorsiflexion when walking backward in water.

There was no significant difference in the muscle activities from the gastrocnemius when walking backward or forward in water, except at moderate speed without a water current. When walking backward, the soleus is known to be inactive, whilst its antagonist, the tibialis anterior is known to be active [23]. The present findings, showing increased muscle activity from the tibialis anterior and insignificant muscle activity from the gastrocnemius while walking backward in water support the findings observed on dry land [23]. The insignificant difference in muscle activities from the gastrocnemius may be due to the reciprocal innervation of increased muscle activity from the tibialis anterior while walking backward in water.

It is worth noting that the %MVCs from the tested muscles increased with increasing speed. Walking backward at moderate and fast speed, produced approximately 40% and 110% greater muscle activity than at slow speed, respectively. Resistance in water is related to the speed of movement, and it increases as the square of speed [24]. The increased %MVCs may be related to the muscle masses activated to maintain the pace as speed increases, or may simply be a reflection of the greater resistance to movements encountered in water [24].

HR responses tended to be greater while walking backward than when walking forward, which reached statistical significance at fast speed, with a water current. This supports previous findings observed on dry land [8,12]. Possible explanations for this increased HR while walking backward in water can only be considered based on the findings obtained on dry land, because no data comparing HR responses while walking backward and forward in water are available. Firstly, the increased cardiorespiratory response while walking backward can be attributed to the execution of an unfamiliar task [12], since backward locomotion is a novel task for most individuals [13]. Economy of motion in a novel activity may require increasingly greater motor unit requirements, thus increasing the energy and oxygen demand at the tissue level in order to complete the task [25]. Secondly, alteration of stride length and frequency may be a possible reason for increased cardiorespiratory response, since it has been shown that stride length is shorter when walking backward than when walking forward [8,12]. Thirdly, when walking backward, the quadriceps muscle acts more concentrically, compared to the more eccentric pattern seen when walking forward [8,11]. Finally, walking backward produces higher blood lactate concentrations than walking forward, thereby suggesting a larger anaerobic component with the former, which may perhaps contribute to a higher cardiorespiratory demand . [8,12]. In addition, the HR increased as speed increased. This is consistent with the previously reported findings of Hall et al. [24]. Further investigations to evaluate cardiorespiratory and biomechanical responses while walking backward in water are needed, however, before drawing any definitive conclusions.

5. Conclusion

The present study demonstrated that the muscle activities from the paraspinal muscles, vastus medialis, and tibialis anterior while walking backward were significantly greater than when walking forward (both with and without a water current). Additionally, HR responses tended to be greater while walking backward in water than when walking forward, with a statistical significance at fast speed. These data offer important implications for the design and application of rehabilitation and exercise programs that include walking backward in water. Furthermore, the methodology presented in the current study should enable a future comparison of normal and pathological gait patterns in water.

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References

[1] Fernhall B, Manfredi TG, Congdon K. Prescribing water-based exercise from treadmill and arm ergometry in cardiac patients. Med Sci Sports Exerc 1992;24:139–43.
[2] Evans BW, Cureton KJ, Purvis JW. Metabolic and circulatory responses to walking and jogging in water. Res Q Exerc Sport 1978;49:442–9.
[3] Oda S, Matsumoto T, Nakagawa K, Moriya K. Relaxation effects in humans of underwater exercise of moderate intensity. Eur J Appl Physiol 1999;80:253–9.
[4] Campbell JA, D'Acquisto LJ, D'Acquisto DM, Cline MG. Metabolic and cardiovascular response to shallow water exercise in young and older women. Med Sci Sport Exerc 2003;35:675–81.
[5] Castellani JW, Young AJ, Kain JE, Sawka MN. Thermoregulatory responses to cold water at different times of day. J Appl Physiol 1999;87:243–6.
[6] Whitley JD, Schoene LL. Comparison of heart rate responses: water walking versus treadmill walking. Phys Ther 1987;67:1501–4.
[7] Masumoto K, Takasugi S, Hotta N, Fujishima K, Iwamoto Y. Electromyographic analysis of walking in water in healthy humans. J Physiol Anthropol Appl Human Sci 2004;23:119–27.
[8] Hooper TL, Dunn DM, Erick Props J, Bruce BA, Sawyer SF, Daniel JA. The effects of graded forward and backward walking on heart rate and oxygen consumption. J Orthop Sports Phys Ther 2004;34:65–71.
[9] Flynn TW, Soutas-Little RW. Mechanical power and muscle action during forward and backward running. J Orthop Sports Phys Ther 1993;17:108–12.
[10] Threlkeld AJ, Horn TS, Wojtowicz GM, Rooney JG, Shapiro R. Kinematics, ground reaction force, and muscle balance produced by backward running. J Orthop Sports Phys Ther 1989;11:56–63.
[11] Flynn TW, Soutas-Little RW. Patellofemoral joint compressive forces in forward and backward running. J Orthop Sports Phys Ther 1995;21:277–82.
[12] Flynn TW, Connery SM, Smutok MA, Zeballos RJ, Weisman IM. Comparison of cardiopulmonary responses to forward and backward walking and running. Med Sci Sports Exerc 1994;26:89–94.

[13] Myatt G, Baxter R, Dougherty R, Williams G, Halle J, Stetts D, Underwood F. The cardiopulmonary cost of backward walking at selected speeds. J Orthop Sports Phys Ther 1995;21:132–8.
[14] Chaloupka EC, Kang J, Mastrangelo MA, Donnelly MS. Cardiorespiratory and metabolic responses during forward and backward walking. J Orthop Sports Phys Ther 1997;25:302–6.
[15] Williford HN, Olson MS, Gauger S, Duey WJ, Blessing DL. Cardiovascular and metabolic costs of forward, backward, and lateral motion. Med Sci Sports Exerc 1998;30:1419–23.
[16] Winter DA, Pluck N, Yang JF. Backward walking: a simple reversal of forward walking? J Mot Behav 1989;21:291–305.
[17] Hislop HJ, Montgomery J. Daniel's and Worthingham's muscle testing: Techniques of manual examination, 6th ed., Philadelphia: WB Saunders; 1995.
[18] Sheldahl LM, Wann LS, Clifford PS, Tristani FE, Wolf LG, Kalbfleisch JH. Effect of central hypervolemia on cardiac performance during exercise. J Appl Physiol 1984;57:1662–7.
[19] Takeshima N, Rogers ME, Watanabe E, Brechue WF, Okada A, Yamada T, Islam MM, Hayano J. Water-based exercise improves health-related aspects of fitness in older women. Med Sci Sports Exerc 2002;34:544–51.
[20] Cole AJ, Moschetti M, Eagleston RE. Lumbar spine aquatic rehabilitation: A sports medicine approach. Rehab Manag 1996;9(55–60):62.
[21] DeVita P, Stribling J. Lower extremity joint kinetics and energetics during backward running. Med Sci Sports Exerc 1991;23:602–10.
[22] Cipriani DJ, Armstrong CW, Gaul S. Backward walking at three levels of treadmill inclination: an electromyographic and kinematic analysis. J Orthop Sports Phys Ther 1995;22:95–102.
[23] Schneider C, Capaday C. Progressive adaptation of the soleus H-reflex with daily training at walking backward. J Neurophysiol 2003;89: 648–56.
[24] Hall J, Macdonald IA, Maddison PJ, O'Hare JP. Cardiorespiratory responses to underwater treadmill walking in healthy females. Eur J Appl Physiol 1998;77:278–84.
[25] Schwane JA, Johnson SR, Vandenakker CB, Armstrong RB. Delayed-onset muscular soreness and plasma CPK and LDH activities after downhill running. Med Sci Sports Exerc 1983;15:51–6.