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Physiological and perceptual responses to backward and forward treadmill walking in water

Kenji Masumoto [a,*], Ayako Hamada [b], Hiro-omi Tomonaga [c], Kana Kodama [b], Yuko Amamoto [b], Yoshiko Nishizaki [b], Noboru Hotta [a]

[a] Institute of Health Science, Kyushu University, 6-1 Kasuga-koen, Kasuga, Fukuoka 816-8580, Japan
[b] Graduate School of Human-Environment Studies, Kyushu University, Fukuoka, Japan
[c] Tomonaga Clinic of Internal Medicine, Nagasaki, Japan

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ABSTRACT

We compared physiological and perceptual responses, and stride characteristics while walking backward in water with those of walking forward in water. Eight males walked on an underwater treadmill, immersed to their xiphoid process level. Oxygen uptake ($\dot{V}_{O_2}$), respiratory exchange ratio (R), heart rate (HR), minute ventilation ($\dot{V}_E$), blood lactate concentration (BLa), ratings of perceived exertion (RPE: for breathing and legs, RPE-Br and RPE-Legs, respectively), blood pressure (for systolic and diastolic pressures, SBP and DBP, respectively), and step frequency (SF) were measured. In addition, step length (SL) was calculated. $\dot{V}_{O_2}$, R, HR, $\dot{V}_E$, BLa, RPE-Br, RPE-Legs, and SBP were significantly higher while walking backward in water than when walking forward in water ($P < 0.05$). Furthermore, SF was significantly higher ($P < 0.001$) and SL was significantly lower ($P < 0.001$) while walking backward in water, compared to walking forward in water. These results indicate that walking backward in water elicits higher physiological and perceptual responses than those produced when walking forward in water at the same speed.

1. Introduction

Walking as a form of exercise is popular among water exercise programs. When walking in water, there is a demand for locomotion not only in a forward direction but also in various other directions [1,2]. It has been noted that backward locomotion is a beneficial mode of exercise, which could be included in rehabilitation and exercise programs. When compared with forward locomotion, backward locomotion reduces the peak patellofemoral joint compressive forces [3], however, it increases muscle activity [4] and quadriceps strength [5]. Furthermore, backward locomotion has been shown to produce higher cardiopulmonary responses than forward locomotion [6–8].

Recently, Masumoto et al. [1] reported that activation of the paraspinal muscles, vastus medialis, and tibialis anterior is higher when walking backward in water than when walking forward in water. However, there is a striking lack of information about physiological and perceptual responses, and about stride characteristics when walking backward in water. Such information is necessary to improve understanding of the locomotor mechanics during walking in water. For this purpose, we compared oxygen consumption ($\dot{V}_{O_2}$), respiratory exchange ratio (R), heart rate (HR), minute ventilation ($\dot{V}_E$), blood pressure (SBP and DBP for systolic and diastolic blood pressures, respectively), blood lactate concentration (BLa), ratings of perceived exertion (RPE: RPE-Br and RPE-Legs, for breathing and legs, respectively), step frequency (SF), and step length (SL) while walking backward in water, with those noted when walking forward in water. We used an underwater treadmill in an effort to ascertain the influence of the existence of a current on the physiological and perceptual responses while walking backward in water.

We hypothesized that the physiological and perceptual responses would be higher when walking backward in water than when walking forward in water [1,6–9]. It was further hypothesized that SF would be higher and that SL would be lower when walking backward in water than when walking forward in water [7,8].

2. Methods

2.1. Subjects

Eight healthy male subjects participated in this study (mean ± S.D.: age, 22.5 ± 2.8 years; height, 173.7 ± 4.2 cm; body mass, 65.8 ± 4.8 kg). The subjects were all physically active individuals, and they were free from any acute or chronic disease at the time of the study. The study was approved by the university ethics

* Corresponding author. Tel.: +81 92 583 7685; fax: +81 92 592 2866.
E-mail address: masumoto@ihs.kyushu-u.ac.jp (K. Masumoto).

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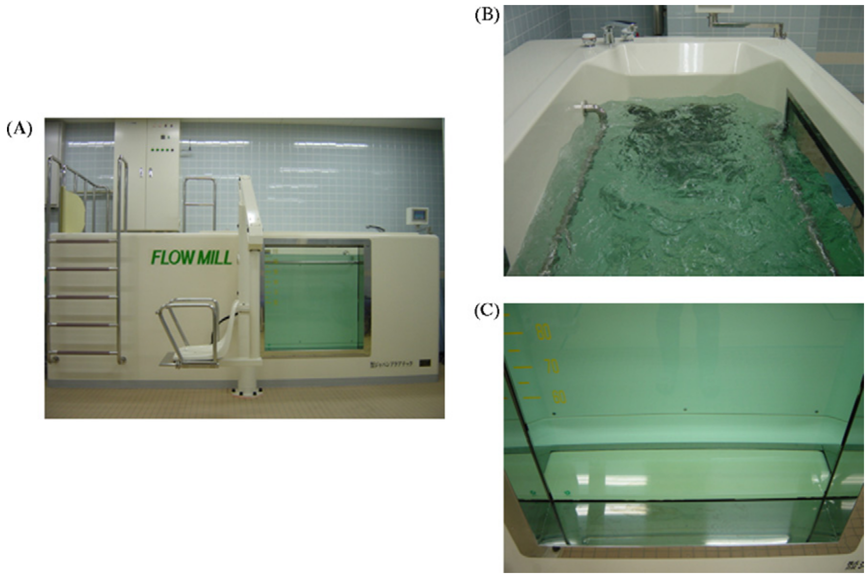

Fig. 1. Pictures of the Flowmill (A), water current (B), and the treadmill in water (C).

committee, and written informed consent to participate in the study was obtained from all subjects.

2.2. Measurements

Metabolic variables ($\dot{V}_{O_2}$, R, and $\dot{V}_E$) were continuously measured using a portable, breath-by-breath gas analyzer (K4b^2, Cosmed, Italy) and data from the final 30 s of every stage were analyzed [10]. Before each test, the gas analyzers were calibrated using known ambient air and sample gas references, and the turbine flowmeter of the system was calibrated with a syringe of known volume. The HR was recorded continuously with a Polar portable device (Polar Electro, Kempele, Finland), and was analyzed during the last 30 s of each stage [11]. Blood samples were taken from the ear lobe and subsequently analyzed for BLa with a lactate analyzer (LT-1710, Arkray, Japan). The blood samples were obtained prior to the tests and at the final minute of each exercise bout [11]. The SBP and DBP responses, measured at rest and immediately after the exercise session with the left arm held horizontal at the level of the heart, were recorded using a manual sphygmomanometer [12]. The RPE was measured using Borg's 6-20 scale [13] for breathing (RPE-Br) and legs (RPE-Legs) separately during the final minute of each exercise bout [12]. The SF was measured for 60 s during the final minute of each exercise bout [11]. The SL was calculated by dividing the distance traveled by SF [11].

2.3. Experimental procedures

Each subject completed all the exercise tests within a single day. The trials consisted of walking backward in water and walking forward in water, both with and without a water current [1]. Subjects walked on an underwater treadmill (Flowmill, FM-1200D, Japan Aqua Tech, Japan; Fig. 1), immersed to their xiphoid process level [1,11]. Throughout the experiment, the water temperature of the underwater treadmill was maintained at 31 °C [1,11]. The room temperature was maintained at 26 °C [1,11].

Before commencing the tests, all subjects practiced walking in water at various speeds until confident enough to proceed with the actual measurements [1,11]. Furthermore, the subjects received instructions on the use of the RPE, prior to beginning the actual measurements. Following familiarization trials, the subjects were asked to rest in a seated position for 10 min on dry land. Resting physiological data were obtained in water for 5 min, prior to beginning each test. Actual measurements commenced after the subjects had rested, in order to ensure that their HR had recovered to its pre-exercise level [11]. The walking speeds in water were set at 1.8 km h^{-1}, 2.4 km h^{-1}, and 3.0 km h^{-1} [1]. The speeds of the water current were 1.8 km h^{-1}, 2.4 km h^{-1}, and 3.0 km h^{-1}, in line with the speeds of the underwater treadmill [1]. During the trials with a current, the subjects always walked against the current, with it streaming against their chest during forward locomotion and against their back during backward locomotion. Each subject completed 4 min exercise bouts at each speed for each condition, with a 1 min rest period between each of the three speed settings [11]. A randomized testing order for the walking conditions (walking forward and backward in water, and walking in water with and without a current) was used in order to minimize threats to the internal validity of the study. There was at least a 30–45 min rest period between the testing conditions. The subjects wore swimsuits throughout the experimental sessions [1,11].

2.4. Statistical analysis

Data are expressed as means ± S.D. All parameters were analyzed using repeated measures ANOVA (factors; walking directions and walking speeds), with the Bonferroni's *post hoc* tests. For all statistical comparisons, the level of significance was set at $P < 0.05$.

3. Results

There was no significant difference in the $\dot{V}_{O_2}$, R, HR, $\dot{V}_E$, and BLa between the backward and forward conditions at rest (Table 1).

As presented in Table 2, $\dot{V}_{O_2}$, R, HR, $\dot{V}_E$, BLa, RPE-Br, and RPE-Legs while walking backward (both with and without a current) were significantly higher than when walking forward in water at all speeds ($P < 0.05$). Additionally, RPE-Legs was significantly higher than RPE-Br while walking backward in water at 2.4 km h^{-1} and 3.0 km h^{-1} ($P < 0.05$) (Table 2). Furthermore, SF was significantly higher ($P < 0.001$) and SL was significantly lower ($P < 0.001$) while walking backward in water, compared to walking forward in water at all speeds (both with and without a current) (Table 3).

The SBP and DBP for each condition are presented in Fig. 2. No significant difference was noted in the SBP and DBP obtained at rest between the forward and backward conditions. Both with and without a water current, the SBP obtained while walking backward in water was significantly higher than that obtained while walking forward in water, at all speeds ($P < 0.01$), although there was no significant difference in DBP under any

Table 1
Physiological responses at rest for each condition

Variables	Water + cur		Water – cur	
	Forward	Backward	Forward	Backward
$\dot{V}_{O_2}$ (ml kg^{-1} min^{-1})	5.4 ± 1.0	5.7 ± 1.2	5.4 ± 1.1	5.6 ± 1.0
R	0.67 ± 0.03	0.68 ± 0.04	0.68 ± 0.03	0.69 ± 0.04
HR (beats min^{-1})	70.0 ± 8.2	68.9 ± 8.2	71.0 ± 6.8	70.9 ± 7.0
$\dot{V}_E$ (l min^{-1})	10.7 ± 3.2	10.9 ± 3.3	9.9 ± 1.2	11.3 ± 2.3
BLa (mmol l^{-1})	0.9 ± 0.1	1.0 ± 0.1	0.9 ± 0.1	0.9 ± 0.1

Water + cur, walking in water with a current; water – cur, walking in water without a current; forward, forward walking in water; backward, backward walking in water; $\dot{V}_{O_2}$, oxygen consumption; R, respiratory exchange ratio; HR, heart rate; $\dot{V}_E$, minute ventilation; BLa, blood lactate concentration. Values are mean ± S.D.

Table 2
Physiological and perceptual responses while walking backward in water and while walking forward in water, with and without a water current

Variables	1.8 km h^{-1}				2.4 km h^{-1}				3.0 km h^{-1}			
	Water + cur		Water − cur		Water + cur		Water − cur		Water + cur		Water − cur	
	Forward	Backward	Forward	Backward	Forward	Backward	Forward	Backward	Forward	Backward	Forward	Backward
$\dot{V}_{O_2}$ (ml kg^{-1} min^{-1})	9.6 ± 1.9	14.1 ± 2.5***	7.5 ± 1.7	10.9 ± 2.1**	12.6 ± 1.9	19.2 ± 2.4***	9.4 ± 2.0	14.2 ± 2.3***	18.8 ± 2.2	28.7 ± 3.4***	15.5 ± 2.1	23.1 ± 2.3***
R	0.73 ± 0.04	0.80 ± 0.04**	0.68 ± 0.04	0.74 ± 0.04*	0.77 ± 0.06	0.85 ± 0.07**	0.73 ± 0.06	0.79 ± 0.06*	0.86 ± 0.07	0.91 ± 0.07*	0.79 ± 0.04	0.84 ± 0.05*
HR (beats min^{-1})	92.1 ± 6.6	113.1 ± 7.4***	82.9 ± 8.6	101.8 ± 9.3***	101.1 ± 6.9	126.4 ± 8.9***	92.3 ± 9.8	114.7 ± 9.5***	120.9 ± 6.8	149.7 ± 10.2***	109.9 ± 6.7	136.9 ± 8.4***
$\dot{V}_E$ (l min^{-1})	16.1 ± 3.3	25.7 ± 5.9***	12.6 ± 2.5	18.2 ± 4.4*	23.5 ± 4.1	39.6 ± 7.5***	18.2 ± 4.1	26.3 ± 7.7**	34.7 ± 3.8	58.3 ± 7.3***	26.1 ± 4.7	43.8 ± 9.4***
BLa (mmol 1^{-1})	1.1 ± 0.1	1.5 ± 0.2***	1.0 ± 0.1	1.2 ± 0.1*	1.3 ± 0.2	2.2 ± 0.3***	1.1 ± 0.2	1.6 ± 0.3***	1.4 ± 0.2	3.4 ± 0.2***	1.2 ± 0.2	2.6 ± 0.4***
RPE-Br	8.9 ± 1.0	11.1 ± 1.0**	7.9 ± 0.8	9.4 ± 0.9*	10.0 ± 1.3	12.1 ± 1.7**	8.9 ± 1.1	10.4 ± 1.2*	11.3 ± 1.8	13.1 ± 1.9**	10.0 ± 1.6	11.4 ± 1.5*
RPE-Legs	9.0 ± 0.9	12.0 ± 1.9***	7.6 ± 0.7	10.1 ± 1.5***	10.3 ± 0.9	13.9 ± 1.6***,††	8.9 ± 0.8	11.6 ± 1.4***	11.5 ± 0.8	15.1 ± 1.6***,††	10.0 ± 1.1	13.0 ± 1.1***,†

Water + cur, walking in water with a current; water − cur, walking in water without a current; forward, forward walking in water; backward, backward walking in water; $\dot{V}_{O_2}$, oxygen consumption; R, respiratory exchange ratio; HR, heart rate; $\dot{V}_E$, minute ventilation; RPP, BLa, blood lactate concentration; RPE-Br and RPE-Legs, ratings of perceived extension for breathing and legs, respectively. Values are mean ± S.D. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$, backward walking vs. forward walking with in each speed condition. $^{\dagger}P < 0.05$, $^{\dagger\dagger}P < 0.01$, RPE-Br vs. RPE-Legs.

Table 3
Step frequency and step length while walking backward in water and while walking forward in water, with and without a water current

Conditions	Step frequency (steps min^{-1})	Step length (m)
1.8 km h^{-1}		
Water + cur		
Walking forward	58.4 ± 2.8	0.51 ± 0.02
Walking backward	67.1 ± 3.2***	0.45 ± 0.02***
Water − cur		
Walking forward	55.5 ± 2.5	0.54 ± 0.02
Walking backward	62.4 ± 2.1***	0.48 ± 0.02***
2.4 km h^{-1}		
Water + cur		
Walking forward	64.8 ± 3.2	0.62 ± 0.03
Walking backward	72.9 ± 2.6***	0.55 ± 0.02***
Water − cur		
Walking forward	61.5 ± 1.6	0.65 ± 0.02
Walking backward	68.0 ± 2.7***	0.59 ± 0.03***
3.0 km h^{-1}		
Water + cur		
Walking forward	69.3 ± 2.4	0.72 ± 0.03
Walking backward	80.9 ± 2.9***	0.62 ± 0.02***
Water − cur		
Walking forward	65.6 ± 1.7	0.76 ± 0.02
Walking backward	74.3 ± 2.5***	0.67 ± 0.02***

Water + cur, walking in water with a current; water − cur, walking in water without a current. Values are mean + S.D. $^{***}P < 0.001$, walking backward vs. walking forward within each speed condition.

of the conditions. The SBP obtained at each speed was significantly higher after exercise, for all conditions ($P < 0.05$), although there was no significant difference in DBP under any of the conditions.

4. Discussion

The major finding of this study was that $\dot{V}_{O_2}$, R, HR, $\dot{V}_E$, BLa, RPE-Br, RPE-Legs, and SBP were higher while walking backward in water than when walking forward in water, both with and without a current. These findings are congruent with previous analyses comparing backward and forward locomotion on dry land [6–9]. In this study, $\dot{V}_{O_2}$, HR, and $\dot{V}_E$ each had means that were 51%, 24% and 65%, and 48%, 24% and 52% higher during backward walking in water than during forward walking in water, with and without a water current, respectively. Earlier studies [6–9] also reported a similar trend of differences in $\dot{V}_{O_2}$, HR, and $\dot{V}_E$ between backward and forward locomotion on dry land (an increase of 28–79%, 17–47%, and 68–101% for $\dot{V}_{O_2}$, HR, and $\dot{V}_E$, respectively).

Firstly, our findings of higher physiological and perceptual responses while walking backward in water compared to those noted when walking forward in water could be due to the performance of an unfamiliar task [7], since backward locomotion is a novel task for most individuals [14]. Hooper et al. [9] hypothesized that backward locomotion may be considered a novel task when performed continuously on a treadmill. Even after the subjects have become familiarized with the experimental protocols, backward locomotion may still be perceived as reasonably new by those same subjects [6]. Schwane et al. [15] reported that a novel activity may require increasingly higher motor unit requirements, therefore increasing the energy costs, in order to complete the task. Clarification of the definitive contribution of physiological and perceptual parameters and task familiarity will require additional research.

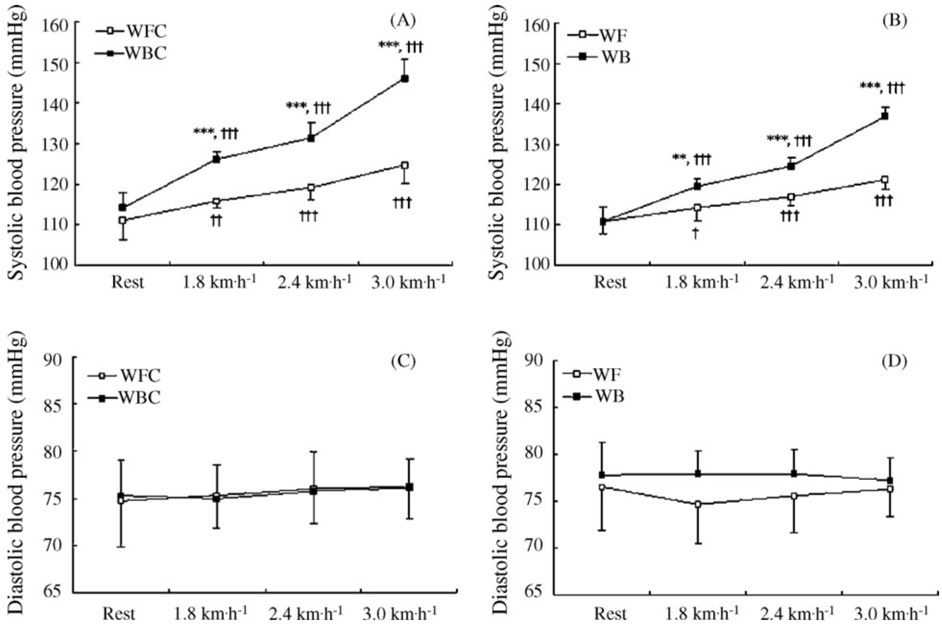

Fig. 2. Systolic (A and B) and diastolic (C and D) blood pressures during the trials. WFC, forward walking with a current; WBC, backward walking with a current; WF, forward walking without a current; WB, backward walking without a current. $^{**}P < 0.01$, $^{***}P < 0.001$, backward walking vs. forward walking within each speed condition. $^{\dagger}P < 0.05$, $^{\dagger\dagger}P < 0.01$, $^{\dagger\dagger\dagger}P < 0.001$, at rest vs. each speed condition.

Secondly, the increased SF (mean increase, 13%) and decreased SL (mean decrease, 12%) while walking backward in water compared to walking forward in water may be contributing factors toward the increased physiological and perceptual responses measured in this study. Increased stride frequency and decreased stride length during backward locomotion compared to those noted during forward locomotion on dry land have also been reported [7,8]. Hooper et al. [9] suggested that subjects may experience an increased cardiopulmonary response when the stride length is shortened, because of the optimal length–tension relationship of muscle. Cavanagh and Williams [16] reported that a 0.185 m reduction in stride length resulted in a mean increase in $\dot{V}_{O_2}$ of 2.6 ml kg^{-1} min^{-1}. In this study, the SL while walking backward in water had a mean of 0.073 m less than when walking forward in water, but it resulted in a 6.1 ml kg^{-1} min^{-1} mean increase in $\dot{V}_{O_2}$. It is difficult to directly compare these findings during locomotion on dry land with the present results of locomotion in water. However, the results of this study appear to indicate a similar trend: decreased SL appears to result in increased $\dot{V}_{O_2}$. Since the biomechanics of walking in water is an emerging area of research [2], further kinematic and kinetic studies are imperative to better describe the actual mechanism behind differences in SF and SL when walking backward in water and when walking forward in water.

Lastly, the increased physiological and perceptual responses while walking backward in water compared to walking forward in water may also be explained in part by the different action of various muscle groups. Chaloupka et al. [6] hypothesized that the peripheral muscle requirements are different during backward or forward walking. In fact, Masumoto et al. [1] reported that muscle activity was 61% higher for the paraspinal muscles, 83% higher for the vastus medialis and 47% higher for the tibialis anterior while walking backward in water than when walking forward in water. During backward locomotion, the quadriceps acts in a more concentric pattern vs. the more eccentric pattern seen during forward locomotion [4]. Concentric muscle contraction has been shown to produce a higher energy cost than eccentric muscle work [17]. Additionally, the BLa during walking backward in water was approximately 72% higher than when walking forward in water in this study. Flynn et al. [7] also reported a higher lactate level during backward locomotion compared with forward locomotion on dry land. The higher BLa during backward walking in water may be related to the greater concentric quadriceps muscle activation pattern during backward locomotion, compared to forward locomotion [4]. Furthermore, the higher BLa when walking backward in water compared with that observed when walking forward in water suggests that backward locomotion is more reliant upon a higher percentage of anaerobic metabolism when compared to forward locomotion [7]. These observations suggest a larger anaerobic component with the former, which may perhaps contribute to the higher physiological and perceptual responses, which were noted in this study. Additionally, one of the unique perspectives of this study is that RPE-Legs was approximately 12% higher than RPE-Br while walking backward in water, both with and without a current. The actual reason for the increased perceptual response for legs than for breathing when walking backward in water is not clear. However, it may be related to the increased muscle activations from the vastus medialis and tibialis anterior while walking backward in water than when walking forward in water [1], or it may be related to the quadriceps fatigue experienced by the subjects during backward locomotion [14].

We observed higher SBP after walking forward and backward in water compared with resting. An increased SBP after exercise in water (e.g., cycle ergometry exercise [18], walking [12]) has also been reported. On the other hand, in this study, the DBP did not change after walking forward and backward in water (both with and without a current) at 31 °C. Hall et al. [12] reported that DBP did not change after walking on dry land and in water at 28.2 °C, but they noted that it decreased in water at 35.8 °C, due to the vasodilation resulting from warm water immersion. The non-significant change in the DBP noted in the present study may be related to the different water temperature employed. A similar experiment carried out in warmer water could result in different findings. Further research to evaluate BP responses during walking in water would be a noteworthy assignment.

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Conflict of interest

None.

References

[1] Masumoto K, Takasugi S, Hotta N, Fujishima K, Iwamoto Y. A comparison of muscle activity and heart rate response during backward and forward walking on an underwater treadmill. Gait Posture 2007;25(2):222–8.
[2] Masumoto K, Mercer JA. Biomechanics of human locomotion in water: an electromyographic analysis. Exerc Sport Sci Rev 2008;36(3):160–9.
[3] Flynn TW, Soutas-Little RW. Patellofemoral joint compressive forces in forward and backward running. J Orthop Sports Phys Ther 1995;21(5): 277–82.
[4] Flynn TW, Soutas-Little RW. Mechanical power and muscle action during forward and backward running. J Orthop Sports Phys Ther 1993;17(2):108–12.
[5] 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(2):56–63.
[6] Chaloupka EC, Kang J, Mastrangelo MA, Donnelly MS. Cardiorespiratory and metabolic responses during forward and backward walking. J Orthop Sports Phys Ther 1997;25(5):302–6.
[7] 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(1):89–94.
[8] 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(9):1419–23.
[9] Hooper TL, Dunn DM, Props JE, 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(2):65–71.
[10] Schiffer T, Knicker A, Hoffman U, Harwig B, Hollmann W, Struder HK. Physiological responses to nordic walking, walking and jogging. Eur J Appl Physiol 2006;98(1):56–61.
[11] Masumoto K, Shono T, Hotta N, Fujishima K. Muscle activation, cardiorespiratory response, and ratings of perceived exertion in older subjects while walking in water and on dry land. J Electromyogr Kinesiol 2008;18(4):581–90.
[12] Hall J, Macdonald IA, Maddison PJ, O'Hare JP. Cardiorespiratory responses to underwater treadmill walking in healthy females. Eur J Appl Physiol 1998; 77(3):278–84.
[13] Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982;14(5):377–81.
[14] 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(3):132–8.
[15] 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(1):51–6.
[16] Cavanagh PR, Williams KR. The effect of stride length variation on oxygen uptake during distance running. Med Sci Sports Exerc 1982;14(1):30–5.
[17] Abbott BC, Bigland B, Ritchie JM. The physiological cost of negative work. J Physiol 1952;117(3):380–90.
[18] Christie JL, Sheldahl LM, Tristani FE, Wann LS, Sager KB, Levandoski SG, et al. Cardiovascular regulation during head-out water immersion exercise. J Appl Physiol 1990;69(2):657–64.