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Original research

The development of an estimation model for energy expenditure during water walking by acceleration and walking speed

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ABSTRACT

Objectives: The aim of this study was to develop an estimation equation for energy expenditure during water walking based on the acceleration and walking speed.
Design: Cross-validation study.
Methods: Fifty participants, males (n = 29, age: 27–73) and females (n = 21, age: 33–70) volunteered for this study. Based on their physical condition water walking was conducted at three self-selected walking speeds from a range of: 20, 25, 30, 35 and 40 m/min. Energy expenditure during each trial was calculated. During water walking, an accelerometer was attached to the occipital region and recorded three-dimensional accelerations at 100 Hz. A stopwatch was used for timing the participant's walking speed. The estimation model for energy expenditure included three components; (i) resting metabolic rate, (ii) internal energy expenditure for moving participants' body, and (iii) external energy expenditure due to water drag force.
Results: When comparing the measured and estimated energy expenditure with the acceleration data being the third component of the estimation model, high correlation coefficients were found in both male (r = 0.73) and female (r = 0.77) groups. When walking speeds were applied to the third component of the model, higher correlation coefficients were found (r = 0.82 in male and r = 0.88 in female). Good agreements of the developed estimation model were found in both methods, regardless of gender.
Conclusions: This study developed a valid estimation model for energy expenditure during water walking by using head acceleration and walking speed.

1. Introduction

The established variables of energy expenditure, oxygen consumption and metabolic equivalent associated with physical activity are fundamental to quantifying activity levels and the subsequent implication on human positive health. The ability to collect this knowledge in real or typical environments, rather than the traditional confines of the laboratory, can be challenging. The compact, unobtrusive and ease of monitoring features of inertial sensor[1] have recently been adopted to monitor activity level during physical activities.[2–4] The sensor can be attached to the human body (e.g. waist, wrist and ankle) and the level of activity determined from this acceleration data.[5–7] Highly accurate estimation models for activity level have been reported,[8–10] along with strong reliability for detecting activity levels.[2–4] However, there was no published study found that reported any estimating models for activity level during water exercise.

Estimation models for energy expenditure previously developed for land-based activities would most likely not be appropriate for water-based activities. This would be due to the 1000-fold difference in density between water and air. Exercising in water requires greater force for movement in order to overcome water drag force, even though gravitational stress on the lower extremity joints is reduced by buoyancy created in water.[11] Consequently, it is hypothesized much higher energy expenditure is required when moving in water, when compared to moving in air.[12–14] For example, For example, to walk at the same metabolic intensity in water compared to land, equates to a third of the walking speed.[12] Moreover, there are differences in: joint moment, ground reaction force, and muscle activity during water-walking compared to land-walking.[11,15,16] Thus, energy expenditure and motion during water-walking differs to that of land-walking. Not only is water exercise widely used for health maintenance/improvement but also for rehabilitation exercise. This is in part due to the physical

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qualities of water compared to air. The buoyancy effect is especially beneficial in obese and disabled people who sometimes have difficulty in moving on land during rehabilitation. Additionally, resistance to movement that is offered by water can increase energy expenditure without adding negative implications that are at times seen in land-based activities e.g. greater loading on the body when running. Therefore, the development of a new estimation model for energy expenditure during water activity would most likely provide useful information for positive health maintenance of this exercise modality.

When considering the estimation model for energy expenditure during water-walking, the effect of water drag force is a dominant component. Surprisingly, almost all of the estimation models that used accelerometry in previous studies did not contain any component of drag force from air.[6,8,10] However, the density of water is approximately 1000 times greater than that of air.[17] Therefore drag effect should not be overlooked in a liquid medium, as may be the case with air-based research. Water drag force increases exponentially with any increase of speed.[18] During water-walking, Kaneda et al.[19] reported that the energy expenditure was influenced by actual walking speed i.e. x^3. Therefore, it is obviously important to contain water drag force in any estimation model for energy expenditure during water-walking. In addition, the method for the component of water drag force should be discussed to develop a much more reliable estimation model. A reliable estimation model would most likely assist in precise exercise prescription and implementation.

The aim of this study was to develop estimation models for energy expenditure during water-walking, and discuss the more valid of the two calculation methods with respect to the water drag force component. The first phase of the research used acceleration data measured by an accelerometer in a similar fashion to the previous land-based studies[5,8,10]; the second phase used actual walking speed as water drag force is largely influenced by speed.[18,19]

2. Methods

Fifty participants, males (n = 29, age: 27–73) and females (n = 21, age: 33–70) freely volunteered for this study. Mean age, height, weight and body mass index of the participants were 55.0 ± 14.9 year, 170.9 ± 6.1 cm, 69.2 ± 9.0 kg, 23.7 ± 3.0 kg/m^2 for males and 57.4 ± 10.7 year, 156.8 ± 4.6 cm, 54.2 ± 5.6 kg, 22.1 ± 2.6 kg/m^2 for females respectively. Written informed consent to participate in the present study was provided and each participant's health status was ascertained by medical history screening and blood pressure measurements prior to commencement of the experiment. All participants were healthy and free of any diseases, without any anamnesis affecting energy expenditure such as abnormal thyroid gland function. This study was approved by the Ethics Committee of Shonan-Fujisawa Campus at Keio University, the status of which is based on the Declaration of Helsinki for the biological and physiological studies.

Participants performed three water-walking trials at an indoor swimming pool (17.2 m length, 5 m width, and 1.1 m depth). Pool walls were constructed to allow surface water to run into gutters, to minimize backwash disturbance in-pool activities. The walking speed for each trial was self-selected by the participants from several velocities: 20, 25, 30, 35 and 40 m/min with these being based on previous research.[19] The subjects walked at each of these velocities before the experiment in order to choose their comfortable velocity. In addition to comfortable velocity, all participants walked at one speed variation above and below their comfortable velocity. To obtain stable energy expenditure measures each trial required a duration of at least 5 min walking. In order to maintain a steady walking speed, a pacesetter walked along the length of

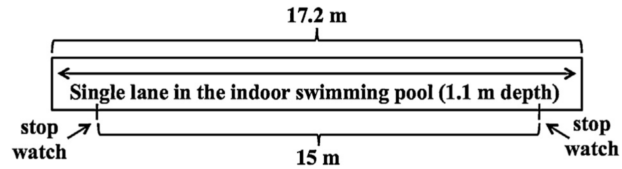

Fig. 1. The swimming pool condition for water-walking.

the of the pool. Each walking trial was separated by at a minimum 5 min recovery period. The subjects' were monitored throughout the experiment to ensure their heart rate had recovered to resting levels before commencing the following trial. Water and air temperatures were maintained throughout the experiment at (30 °C) and (25–28 °C), respectively.

Participant oxygen consumption ($\dot{V}O_2$, l/min/kg) and the carbon dioxide production ($\dot{V}CO_2$, l/min/kg) were measured using the Douglas bag method and a portable gas analyzer (AR-1 O2-ro, Arcosystem Inc., Japan) and a dry gas meter (DCDA-2C-M, Shinagawa Corp., Japan). An accelerometer was attached to the occipital region and recorded three-dimensional accelerations. Capture frequency was 100 Hz. In this study, anteroposterior and longitudinal axis accelerations are used for further analysis due to the walking motion being effectively two-dimensional.[15,16] Time taken to walk between the 1.1 and 16.1 m marks of the pool length was measured using a stopwatch. The 1.1 m before and after the capture area was used for turning. The wall height of the edge of the swimming pool was the same to pool depth (1.1 m). The pool condition was the same as a previous study (Fig. 1).[19]

All $\dot{V}O_2$, $\dot{V}CO_2$ and stopwatch data were collected during the last two round trips of each walking trial. For acceleration data, the last 20 s (not including turning) was collected. Energy expenditure (J/min/kg) was calculated by using the following equation reported by Weir[20] and equation of 1 cal = 4.19 J:

$$\text{energy expenditure} = 3.9 \times \dot{V}O_2 + 1.1 \times \dot{V}CO_2 \quad (1)$$

Walking speed (v_{ww}, m/min) was calculated from stopwatch data. The inclination angle of the accelerometer was calculated from the anteroposterior and longitudinal accelerations (A_y and A_z, as shown in Fig. 2 and Eq. (2)), using a 20 second data sample. This was followed by the use of net anteroposterior and longitudinal accelerations of A_y' and A_z', respectively and was calculated to eliminate the gravity effect (Eqs. (3) and (4)):

$$\theta = \arctan \frac{\overline{A_y}}{\overline{A_z}} \quad (2)$$

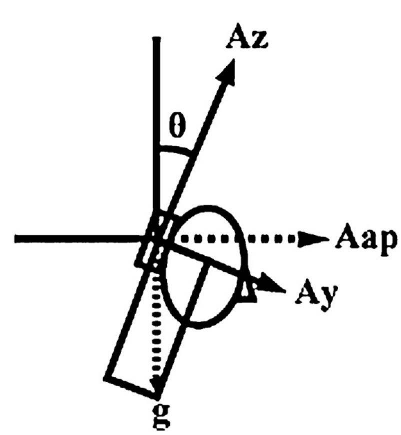

Fig. 2. Collection of the accelerometer. A_z: longitudinal axis acceleration of the accelerometer, A_y: anterior-posterior axis acceleration of the accelerometer, A_{ap}: anterior-posterior acceleration of the head to the walking direction, θ: inclination angle of the accelerometer, g: gravity.