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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 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.

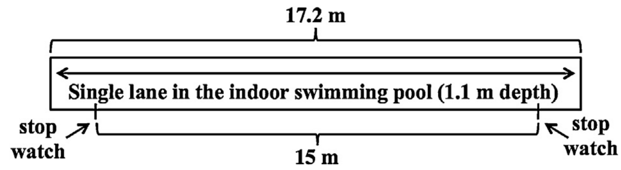

Fig. 1. The swimming pool condition for water-walking.

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)):

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

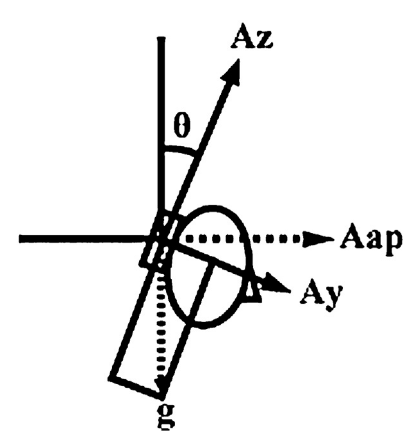

Fig. 2. Collection of the accelerometer. A_z: longitudinal axis acceleration of the accelerometer, A_y: anterior-posterior axis acceleration of the accelerometer, A_{ap}: anterior-posterior acceleration of the head to the walking direction, θ: inclination angle of the accelerometer, g: gravity.

$$A'_y = A_y - g \sin\theta \quad (3)$$

$$A'_z = A_z - g \cos\theta \quad (4)$$

where g was set as 9.8 m/s. Therefore, the anteroposterior acceleration of the head to the walking direction (A_{ap}) was calculated as follows (Fig. 2):

$$A_{ap} = A'_y \cos\theta + A'_z \sin\theta \quad (5)$$

In the present study, the following estimation model for the energy expenditure during water-walking was developed:

$$\text{energy expenditure} = a_0 + a_1 \times RMR + a_2 \times \text{energy expenditure}_i + a_3 \times \text{energy expenditure}_{wd} \quad (6)$$

Where $\alpha_0 \sim \alpha_3$ are coefficients of each component; RMR is the resting metabolic rate; energy expenditure$_j$ is the internal energy expenditure for moving all the joints of the body; and energy expenditure$_{wd}$ is the external energy expenditure for working against water drag force. The RMR (J/min/kg) was calculated by gender and age based on the basal metabolic rate (BMR, J/min/kg) equations in the Dietary Reference Intakes for Japanese[21] and multiplied by 1.2 for the RMR.[22] The dimension of the each component was equivalent to mechanical power due to the energy expenditure during water-walking in the present study being expressed as per unit time. Generally, mechanical power (P) is expressed:

$$P = Fv \quad (7)$$

where F is mechanical force and v is velocity of the object. The mechanical force (F) is expressed:

$$F = ma \quad (8)$$

where m is mass of the object and a is acceleration. Therefore, the mechanical power (P) becomes

$$P = Fv = mav \quad (9)$$

For energy expenditure$_j$, the whole body activity was assumed to be the square root of the sum of A_y' squared and A_z' squared. To determine the 20 second average, data was analyzed in five-second blocks as this enabled one complete stride cycle of water-walking.[16,23]

For energy expenditure$_{wd}$ with acceleration method, A_{ap} was regarded as activity against water drag force. Therefore, energy expenditure$_{wd}$ was calculated as the square root of A_{ap} and averaged by 20 s using the same five-second time stamp blocks as used for energy expenditure$_j$. In addition, energy expenditure$_{wd}$ could also be assumed by using the v_{ww} without A_{ap}. Water drag force (D) is generally expressed in proportion to the square of the moving speed as follows[18]:

$$D = \frac{1}{2} Cd\rho S v^2 \quad (12)$$

where ρ is water density, S is frontal projected area of the object, Cd is coefficient of water drag and v is velocity of the object. Therefore, mechanical power (P) during water-walking as well as energy expenditure$_{wd}$ could be expressed as follows by using formula (7) and (9):

$$P = \text{energy expenditure}_{wd} = Dv_{ww} = \frac{1}{2} Cd\rho S v_{ww}^3 \quad (13)$$

Here, mechanical force (F) is equal to the water drag force (D). Thus, the energy expenditure$_{wd}$ can be expressed to be in proportion to the $v_{ww}{}^3$. In the present study, Cd and S were treated as unknown parameters, and ρ was 1.0.

A multiple regression analysis was made to Eq. (6) for both acceleration and actual walking speed methods applied to energy expenditure$_{wd}$. The analysis was conducted on each male and female group due to energy expenditure (J/min/kg) being influenced by gender during water-walking.[19] Coefficients of each component ($\alpha_0 \sim \alpha_3$), the multiple correlation coefficients (r) and the coefficients of the determination (R^2) were calculated. In addition, for validation a Bland–Altman analysis was applied for bias and 95% limits of agreement of difference between measured and estimated energy expenditure.

3. Results

A total of 150 samples (males: 87, females: 63) were chosen for multiple regression analysis (Fig. 3). The multiple correlation coefficients and the coefficients of the determination were high in both the male (r = 0.73, R^2 = 0.53); energy expenditure = 245.22 − 11.77 RMR + 58.65 energy expenditure$_j$ − 10.16 energy expenditure$_{wd}$ and female groups (r = 0.77, R^2 = 0.60); energy expenditure = 290.07 + 2.98 RMR + 85.48 energy expenditure$_j$ − 26.76 energy expenditure$_{wd}$ when the acceleration method was applied to the energy expenditure$_{wd}$. When the walking speed method was applied to the energy expenditure$_{wd}$, the multiple correlation coefficients were much higher in both the male (r = 0.82, R^2 = 0.68); energy expenditure = 245.22 − 9.14 RMR + 16.09 energy expenditure$_j$ + 42.31 energy expenditure$_{wd}$ and female groups (r = 0.88, R^2 = 0.77); energy expenditure = 290.07 − 7.80 RMR + 28.42 energy expenditure$_j$ + 48.70 energy expenditure$_{wd}$ than those of the acceleration method.

Fig. 4 illustrates the results of the Bland–Altman analysis. Bias and 95% limits of agreement were 00.00 and ±90.32 (J/min/kg) respectively for males with the acceleration method, and 00.00 and ±98.99 (J/min/kg) respectively for the female group. Agreement for the actual walking method, those were – 00.00 and ±74.90 (J/min/kg) for the male, and – 00.00 and ±72.92 (J/min/kg) for the female groups respectively. Almost all of the samples showed good agreement with both estimation models.

4. Discussion

After reviewing the literature, this appears to be the first study that has discussed development of an estimation model for energy expenditure during water-walking. The estimation model is composed of three components: resting metabolic rate; internal energy expenditure for moving all the joints of the participants' bodies (energy expenditure$_j$); and the external energy expenditure for working against the water drag force (energy expenditure$_{wd}$). The wide range of participants that took part in this study provided useful data for water-walking at several speeds The data were: energy expenditure during water-walking; head acceleration, by using accelerometer; and actual walking speed were measured. As a result, both male and female groups showed high estimation correlation coefficients with good agreements of estimation.

Compared with previous studies, the R^2 values of the present study had strong accordance, regardless of gender (0.53–0.77). For example, the R^2 values reported by Hendelman et al.[8] were from 0.59 to 0.78 for walking on land for the metabolic equivalent, and from 0.69 to 0.72 by Rowlands et al.[4] with treadmill walking and running for oxygen consumption. Withers et al.[9] showed 0.57 of the R^2 values with walking on land for the metabolic equivalent. Moreover, the R^2 values of the present study were comparatively higher than that of life related activities reported in the previous studies.[2,5,8] Therefore, the developed estimation model for the energy expenditure during water-walking in the present study would be highly reliable.

The results of the Bland–Altman analysis also indicated good agreement of the estimation model developed in the present study.

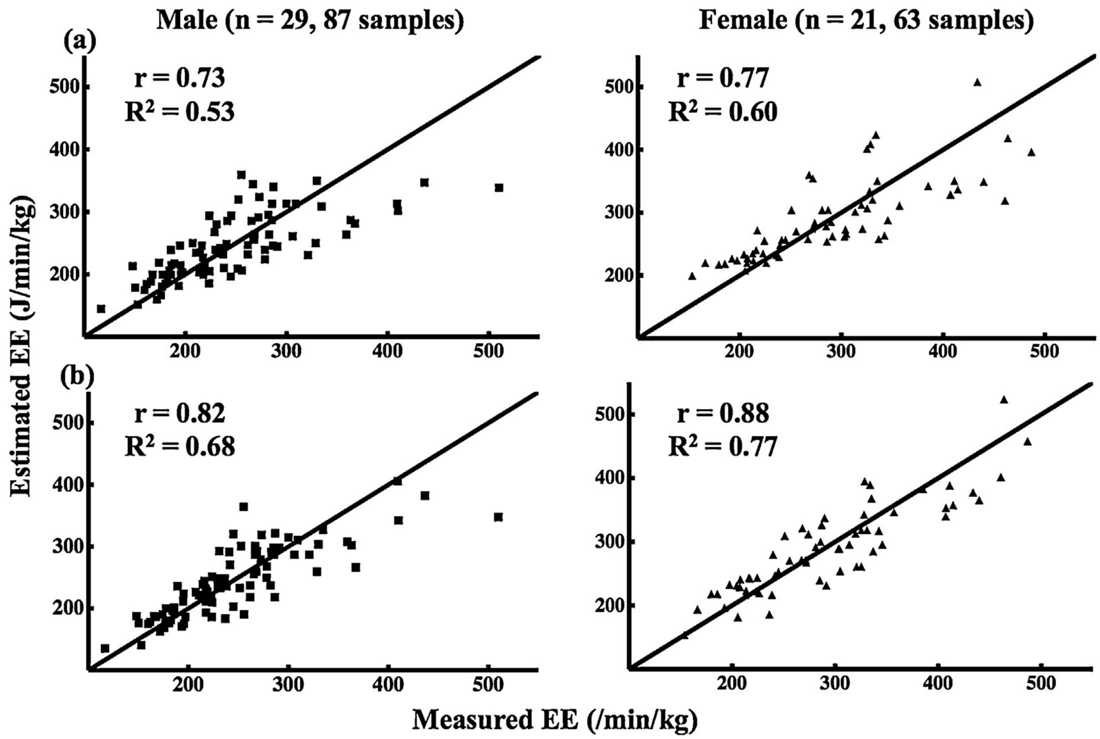

Fig. 3. Relation of the measured EE and estimated EE in both male and female groups with the acceleration method (a) and with the actual walking speed method (b) applied to the third component of the estimation equation. EE: energy expenditure.

Almost all of the sample data were within the 95% limits of agreement in each analysis. This is in accordance with previous studies which reported high prediction models for activity level such as metabolic equivalent and activity count using Bland–Altman analysis.[2,3,10] In addition, minimal bias was shown in each. This indicates the developed estimation model for energy expenditure during water-walking is consistent and appears to be a useful tool in a sample population.[1,24] However, some samples were out of the 95% limits of agreement. For example, the male and female participants who showed larger underestimation values in both

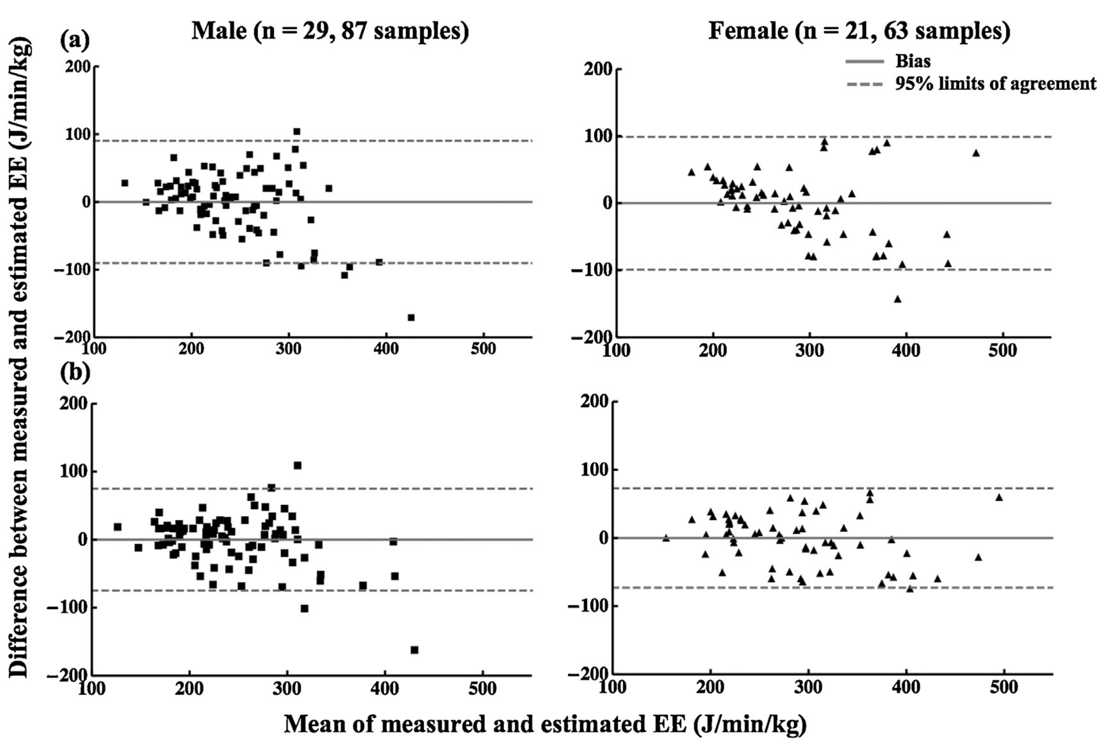

Fig. 4. Bland–Altman plot with indicating bias and agreement in both male and female groups with the acceleration method (a) and with the actual walking speed method (b) applied to the third component of the estimation equation. EE: energy expenditure. Difference was calculated as estimated EE minus measured EE.

acceleration and actual walking speed methods tended to be the faster participants in this trial. The underestimation tendency for energy expenditure in high activity level was also reported in a previous study.[10] The male participants who showed larger overestimation were experienced in competitive swimming. Therefore future investigation into this underestimation would be expected. Such a study may suggest a more reliable estimation model for energy expenditure during water-walking through experiences in water environments that might affect this measure.

This study applied both an acceleration method and also the actual walking method to the energy expenditure$_{wd}$. As a result, the actual walking method showed higher correlation coefficients in both male and female groups than the acceleration method for both sexes. Kaneda et al.[19] reported similar correlation coefficients in estimation of oxygen consumption normalized by participants' weight with actual walking speed (x^3). In addition, the width of the 95% limits of agreement was smaller with the actual walking method than the acceleration method. Thus, the developed estimation model with the actual walking method appears to be more reliable and useful than the model of the acceleration method. The components of energy expenditure$_{wd}$ should not be eliminated when considering an estimation model for energy expenditure during water-walking due to water having specific properties such as buoyancy and water drag force.[11,17] The physiological and biomechanical characteristics also change significantly between water-walking and land-walking.[12,15,16] Therefore, it is important to develop a new estimation model for energy expenditure during water-walking which takes into account water specificities. Although the accelerometer is often developed model used to monitor activity levels due to it being compact, lightweight and easy to use,[2,6,10] further development of a device which measures walking speed as well as acceleration would contribute to a water-based exercise prescriptions for health and physical fitness.

As the acceleration data includes body perturbation and impact force, these factors would probably cause an error of the inclination angle of the accelerometer. This may explain the lower reliability of the acceleration method compared to the actual walking speed method. Further studies may likely solve the error of inclination angle by shape of calculation procedure of the acceleration data. Additionally, this study applied the representative equations for calculating RMR. This method may be influenced by a person's body shape. Therefore possibly affecting the accuracy of energy expenditure. Measuring RMR directly may provide a more accurate estimation equation. Moreover, the present study estimated energy expenditure$_j$ only using the head acceleration data as being representative of the motion of all the joints of the participants' bodies. Increasing the number of accelerometers to measure all the anatomical parts of joint motion would achieve higher reliability than the results of the present study. In the actual walking speed method, the frontal projected area of the immersed body part was not calculated because it continuously changes during water-walking by water and body fluctuations. The frontal projected area is important for estimating the water drag force,[25] and the body shape of the immersed area also affects the water drag force.[17,18] If those parameters could be assumed, the estimation model for energy expenditure during water-walking might have better reliability than the present study. As mentioned above, it is intended that the developed model in this study will be revalidated for appropriate procedures to address and specific groups therefore ensuring reliability of use. There are many forms of water exercise other than walking,[26,27] and can be applied to wide range of populations especially disabled or obese people.[28,29] Therefore these applications can equally be applied to clinical settings during patient rehabilitation. In addition to the development of a more reliable estimation model, further research on other forms of water exercise and different groups would likely contribute to the positive health maintenance of large sections of the population.

5. Conclusion

This study is the first known to develop an estimation model for energy expenditure during water-walking. The estimation model was composed of the resting metabolic rate; the internal energy expenditure for moving all joints for each of the participants' bodies; and the external energy expenditure for working against water drag force. The correlation coefficients of the estimation model showed high value when using the acceleration data for the external energy expenditure. However, higher correlation coefficient values were gained using the walking speed for external energy expenditure. Both methods had good agreement regardless of gender and provides an objective insight for water based exercise and positive health maintenance.

Practical implications

- Energy expenditure during water-walking can be estimated by measuring acceleration and walking speed.
- High intensity energy expenditure tends to underestimate for activities both on land in water.
- Monitoring activity levels using a compact and light-weight unit is possible both on land and in water.

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