A New Device to Estimate $\dot{V}O_2$ during Incline Walking by Accelerometry and Barometry

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ABSTRACT

YAMAZAKI, T., H. GEN-NO, Y. KAMIJO, K. OKAZAKI, S. MASUKI, and H. NOSE. A New Device to Estimate $\dot{V}O_2$ during Incline Walking by Accelerometry and Barometry. *Med. Sci. Sports Exerc.*, Vol. 41, No. 12, pp. 2213–2219, 2009. **Purpose**: To examine whether the biased estimation of oxygen consumption rate ($\dot{V}O_2$, mL·kg^{-1}·min^{-1}) by accelerometry during incline walking can be improved by the addition of altitude changes as measured by barometry. **Methods**: We measured $\dot{V}O_2$ by respiratory gas analysis and vector magnitude (VM, G) from triaxial accelerations in 42 healthy people (mean ± SD age = 63 ± 7 yr) during graded walking on a treadmill while the incline was varied from −15% to +15%. They walked at subjectively slow, moderate, and fast speeds on level and uphill inclines and, in addition to these, at their fastest speed at 0% incline. They then walked at ~3, 4, and 5 km·h^{-1} on downhill inclines for 3 min each. We determined a regression equation to estimate $\dot{V}O_2$ from VM and theoretical vertical upward (H_u, m·min^{-1}) and downward speeds (H_d, m·min^{-1}) for the last 1 min of each trial. To validate the precision of the equation, we measured VM and altitude changes with a portable device equipped with a triaxial accelerometer and a barometer in 11 of the 42 subjects walking on an outdoor hill and compared the estimated $\dot{V}O_2$ with the value simultaneously measured by respiratory gas analysis. **Results**: $\dot{V}O_2$ above resting was estimated from $\dot{V}O_2$ = 0.044 VM + 1.365 H_u + 0.553 H_d (r = 0.93, P < 0.001) and the estimated $\dot{V}O_2(y)$ was almost identical to the measured $\dot{V}O_2(x)$ (y = 0.97x, r = 0.88, P < 0.001) with a mean difference of −0.20 ± 3.47 (mean ± SD) by Bland–Altman analysis in the range of 2.0–33.0 mL·kg^{-1}·min^{-1}. **Conclusions**: $\dot{V}O_2$ during walking on various inclines can be precisely estimated by using the device equipped with a triaxial accelerometer and a barometer. **Key Words:** ACCELEROMETER, BAROMETER, ALTITUDE CHANGE, OUTDOOR WALKING

There are many commercially available devices with a triaxial accelerometer to estimate energy expenditure during walking (6–11,19–21). These can be used to design training regimens to prevent lifestyle-associated diseases and deterioration of physical fitness with advancing age. Indeed, we recently used a self-developed triaxial accelerometer in a 5-month training study on middle-aged and older subjects and found that high-intensity walking (>70% of peak aerobic power) evoked a greater increase in physical fitness and a greater reduction in arterial blood pressure than did moderate-intensity walking (9,16). These results suggested that precise estimation of energy expenditure was useful in accomplishing effective walking training. However, because most of the devices available at present are designed for walking on level ground (3,8,11,14) with no consideration of altitude changes, it is likely that the energy expenditure during uphill walking is underestimated (6,13,14,20) whereas downhill walking is overestimated (13,20). These misestimations have made it difficult to design walking regimens appropriate for individual physical fitness that use inclines and stairs in the living environment.

To solve these problems, Aminian et al. (2) measured triaxial accelerations at the lower back and the heel during walking on various inclines. These accelerometric measurements were entered into their algorithm and proved useful in estimating speed and incline in free-living conditions. Recently, Perrin et al. (18) measured body acceleration with a uniaxial accelerometer, altitude variations with a barometer, and walking speed with a satellite positioning system

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and suggested that the walking speed prediction by accelerations was improved by correction for altitude change. However, because they (18) did not provide any calculation process or technical solution to easily estimate energy expenditure during walking on inclines for various individual physical fitness levels, their results did not lead to the development of any new devices broadly used for this purpose in the field.

In the present study, we examined the hypothesis that the biased estimation of oxygen consumption rate ($\dot{V}O_2$, $mL \cdot kg^{-1} \cdot min^{-1}$) with accelerometry during walking on inclines can be improved by taking into account vertical upward and downward speeds. $\dot{V}O_2$ could be converted to energy expenditure on the basis of some minor assumptions in the field. To do this, we developed a new portable device equipped with a triaxial accelerometer, a barometer, and an algorithm and assessed the possible application of the device during walking in the field at various inclines.

METHODS

Theory

It has been suggested that the energy expenditure during walking on level ground is accurately estimated by a triaxial accelerometer attached to the center of the body mass (3,6,9). However, during uphill walking, additional energy is expended to gain the potential energy to raise the body against gravity, and inversely, during downhill walking, the energy for walking is saved in part by the use of potential energy. Therefore, in the present study, we assumed that the accelerations of body movements and potential energy gain/loss during walking were independent of each other and $\dot{V}O_2$ could be estimated by the following equation:

$$\dot{V}O_2 = k_1 \mathrm{VM} + k_2 H_u + k_3 H_d, \quad [1]$$

where $\dot{V}O_2$ is activity oxygen consumption rate ($mL \cdot kg^{-1} \cdot min^{-1}$), VM (G) is the sum of vector magnitude calculated from triaxial accelerations (see below), H_u is the vertical upward speed ($m \cdot min^{-1}$), and H_d is the vertical downward speed ($m \cdot min^{-1}$). k_1, k_2, and k_3 are coefficients to transform the respective values to $\dot{V}O_2$.

In the treadmill study, the theoretical vertical speed (H) during walking on a positive or negative incline was calculated as,

$$H = v \sin\{\tan^{-1}(s/100)\}, \quad [2]$$

where v is walking speed ($m \cdot min^{-1}$) and s is incline (%).

In the field validation study, the vertical speed during walking was calculated as,

$$H = 18,410(1 + 0.003661 t_v)\{\log(P_1) - \log(P_2)\}, \quad [3]$$

where P_1 and P_2 are barometric pressures (hPa) at two places before and after every 1-min walking, respectively, and t_v is averaged atmospheric temperature (°C) during the measurement (15).

Subjects and Protocol

Treadmill study. The treadmill study was conducted to determine equation 1. The experiment was performed in a test room where atmospheric temperature and relative humidity were controlled at ~25°C and ~50%, respectively. Forty-two middle-aged and older men (n = 21) and women (n = 21) were recruited from participants in a health promotion program for middle-aged and older people in Matsumoto, Japan. Their physical characteristics are shown in Table 1. They had no overt history of cardiovascular or pulmonary diseases and no orthopedic limitations for participating in the experiment. After the protocol, approved by the Institutional Review Board on Human Experiments, Shinshu University School of Medicine, was fully explained, subjects gave written informed consent before participating in the experiment.

All subjects participated in the experiment for 3 d, separated by more than a day between each. On the first day, they reported to the laboratory at 09:30 to 10:00 or at 13:30 to 14:00 well hydrated and having had a light meal more than 90 min previously. Body mass was measured to the nearest 100 g while the subjects wore light clothing and rubber-soled walking shoes. Next, each subject accommodated to treadmill walking by walking on the treadmill at his/her own preferred speed for approximately 20 min. They then rested in a seat for 20 min while a triaxial accelerometer was attached with other devices to measure $\dot{V}O_2$ by respiratory gas analysis and HR ($beats \cdot min^{-1}$) by electrocardiography. Subjects put the accelerometer on the right or left side of the waist on the midclavicular line where they put a pedometer during daily walking. After confirming their $\dot{V}O_2$ had returned to the resting level, they stood still on the treadmill for 3 min and then performed slow, moderate, fast, and fastest speeds of walking for 3 min each in this order on the level setting. The subjective speeds of slow, moderate, and fast walking were ~40%, ~65%, and ~80% of that of their fastest walking speed, respectively. After resting in a seat for 20 min and confirming that their $\dot{V}O_2$ had again returned to the resting level, subjects performed the same protocol but without the fastest walking while varying the incline of the treadmill to –5% and then to +5%.

On the second day, the subjects repeated the same protocol but without the fastest walking while varying the incline of the treadmill to –10% and then to +10% and, on the third day, to –15% and then to +15%. The maximal

TABLE 1. Physical characteristics of subjects.

	Treadmill Study		Field Validation Study	
	Males	Females	Males	Females
n	21	21	8	3
Age (yr)	67 ± 5	59 ± 7	58 ± 11	60 ± 10
Height (cm)	166 ± 4	155 ± 5	167 ± 5	154 ± 3
Body mass (kg)	68 ± 7	57 ± 8	64 ± 7	51 ± 8

Values are means ± SE.

SPECIAL COMMUNICATIONS

downhill walking speed was limited to 5 $km \cdot h^{-1}$ by the treadmill's capability.

During resting and walking on the treadmill, VM, $\dot{V}O_2$, and HR were recorded as described below.

Field validation study. The field validation study was conducted to validate the precision of the regression equation determined by the treadmill study. Eight of the 21 males and 3 of the 21 females in the treadmill study participated in the field validation study. Their physical characteristics are shown in Table 1. They were allowed to choose one of the three outdoor trails described in Table 2 according to their physical fitness levels so that they could finish walking at their own preferred speed within 60 min. Four males chose the no. 1 trail on a hill with the steepest mean incline (14.0%), one male chose the no. 2 trail with medium mean incline (6.3%), and 3 males and 3 females chose the no. 3 trail with the most gradual mean incline (2.5%).

The field validation study was performed from October 25 to November 22 in 2006 during which period the climate conditions were 14 ± 3°C in atmospheric temperature (mean ± SD), 60 ± 7% in relative humidity, with little wind, in fine or cloudy weather. The mean atmospheric pressures (hPa) at the start point were 948 ± 3, 943 ± 0, and 913 ± 4 for trail nos. 1, 2, and 3, respectively. The subjects came to the field at 10:00 or 14:00 h. After body mass was measured again to the nearest 100 g, while the subjects wore similar clothing as before, they walked on level ground at their own preferred speed for ~20 min as a warm-up as done in the treadmill study. Then, after resting in a seat for 20 min, while all measurement devices were applied and confirming $\dot{V}O_2$ had returned to the resting level, they began walking uphill on a zigzag trail, arrived at the summit, and then returned down to the starting point by the trail. During walking, VM, $\dot{V}O_2$, and HR were measured as in the treadmill study. In addition, barometric pressure changes were measured with a barometer. The details are described below.

Measurements

Accelerations and barometric pressures. In the treadmill study and the field validation study, three-dimensional accelerations were measured every 20 ms, averaged, and stored every 5 s in a Jukudai Mate (Kissei Comtec, Matsumoto, Japan), a microprocessor-based device, 80 mm in width, 50 mm in height, 21 mm in depth, and 82 g in weight. The device was equipped with two orthogonally attached dual-axis accelerometers with detection range of ±10G (ADXL210JE; Analog Devices, Wilmington, MA), 4-MB flash memory (MBM29DL322TE-90TN-E1; Fujitsu, Tokyo, Japan) capable of storing minute-by-minute data for 24 h × 60 d, a rechargeable lithium ion battery (UF-1311C; Sanyo, Osaka, Japan) capable of working for 24 h when fully charged, and a USB interface to transfer stored data to an external computer. Also, the device was equipped with a chip to sense barometric pressure with a temperature drift compensation circuit (115 kPa; Fujikura, Tokyo, Japan) for evaluating altitude change, with a detection range of 115–1150 hPa; 90% of its response time is within 2 ms after a change in altitude and the maximal precision is 0.06 hPa or 49 cm of altitude at sea level. Figure 1 shows the precision of estimating altitude changes from atmospheric pressure measured with the chip during climbing up and down stairs 28.8 m in height in a seven-story building at 670 m of altitude. The regression equation between true (x) and estimated (y) altitude is $y = 0.98x + 0.08$ with ±1.41 m for a 95% confidence limit during the measurement.

TABLE 2. Characteristics of the field.

	No. 1	No. 2	No. 3
Horizontal distance to peak (m)	2150	3180	5200
Vertical distance to peak (m)	300	202	130
Start point altitude (m)	610	650	910

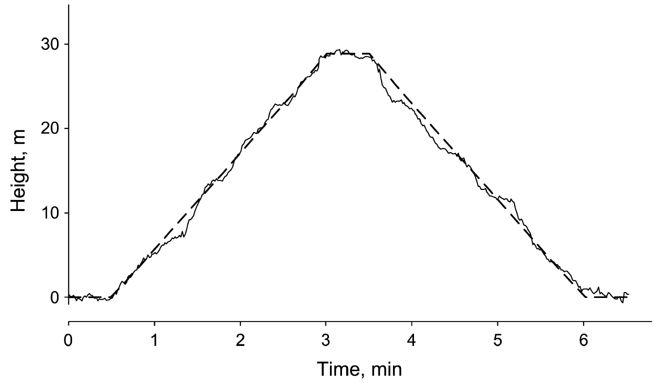

FIGURE 1—An example of altitude changes measured by barometric pressure during climbing up and down stairs 28.8 m in height in a seven-story building at constant speed. The *dashed line* indicates actual altitude change, whereas the *solid line* represents the measured change.

$\dot{V}O_2$ and HR. $\dot{V}O_2$ was measured with MetaMax-3B (CORTEX Biophysik, Leipzig, Germany) both in a test room and in the field. Before the experiment, the analyzers were calibrated by using ambient air and a mixture of 15.98% oxygen and 3.96% carbon dioxide. The volume transducer of the analyzer was calibrated with a 3-L gas syringe. Moreover, before each session of measurement, we confirmed that the analyzer indicated 20.93% oxygen and 0.03% carbon dioxide concentrations during ambient airflow. HR was recorded by electrocardiography (Polar Electro Oy, Kempele, Finland).

Analyses

VM versus $\dot{V}O_2$ in the treadmill study. VM during walking in each trial was calculated as previously reported by us (9). Briefly, total acceleration for 1 s was determined as the square root of the summed square acceleration in each direction, and VM was determined as an integration of total acceleration for the period. Because there were no significant differences in these measurements between males and females in each trial ($P > 0.05$), we determined

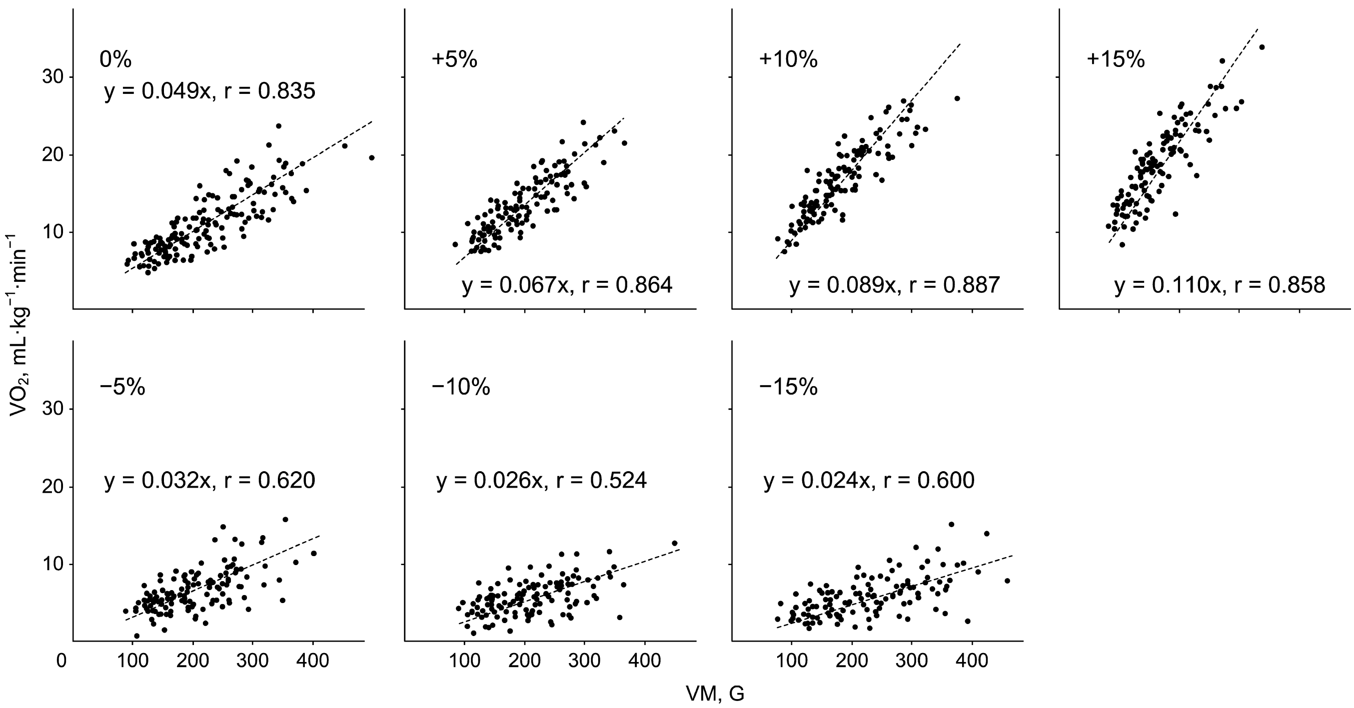

FIGURE 2—Each panel indicates the relationship between oxygen consumption rate ($\dot{V}O_2$) and vector magnitude of triaxial accelerations (VM) for the last 1 min of each walking trial while the incline of the treadmill was changed to 0%, +5%, +10%, +15%, –5%, –10%, and –15% in the treadmill study. $\dot{V}O_2$ and VM were determined by subtracting the values during resting from those during walking. The *dashed line* indicates the regression line for all subjects.

the regression equation between VM and $\dot{V}O_2$ using pooled data from all subjects for each incline of the treadmill (Fig. 2) after subtracting VM and $\dot{V}O_2$ during rest from those during walking.

Derivation of efficiency parameters in the treadmill study. To determine k_1, k_2, and k_3 in equation 1, we performed multiple linear regression analyses by substituting $\dot{V}O_2$ and VM for the last 1 min of walking and also theoretical vertical upward (H_u) and downward speeds (H_d) derived from equation 2. We determined k_1, k_2, and k_3 for each subject and presented them as means and SE for all subjects. Also, we determined the parameters using the pooled data from males and females after confirming no significant differences between them ($P > 0.05$).

$\dot{V}O_2$ estimated from VM, H_u, and H_d in the field validation study. In the field validation study, we estimated $\dot{V}O_2$ every 1 min by substituting VM, H_u, and H_d for equation 1. H_u and H_d were determined from changes of barometric pressure every 1 min so that the gradual change in atmospheric pressure was negligible. Both H_u and H_d were zero during level walking, H_u was positive and H_d was zero during uphill walking, and H_d was negative and H_u was zero during downhill walking.

Statistics

Least squares regression analyses with no intercept were used to determine the relationship between VM and $\dot{V}O_2$ in Figure 2, whereas ANOVA with repeated measures was performed to test any significant differences in regression coefficients between any inclines of the treadmill. The least squares regression equation was determined between measured $\dot{V}O_2$ by respiratory gas analysis and estimated $\dot{V}O_2$ in

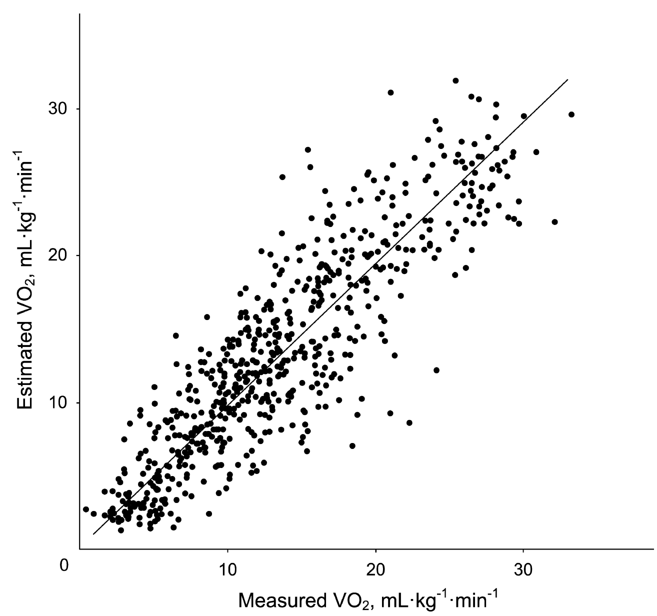

FIGURE 3—Relationship between measured oxygen consumption rate ($\dot{V}O_2$) by respiratory gas analysis and estimated $\dot{V}O_2$ from equation 4 for all 11 subjects during walking in the field. The *solid line* indicates a regression line for all values.

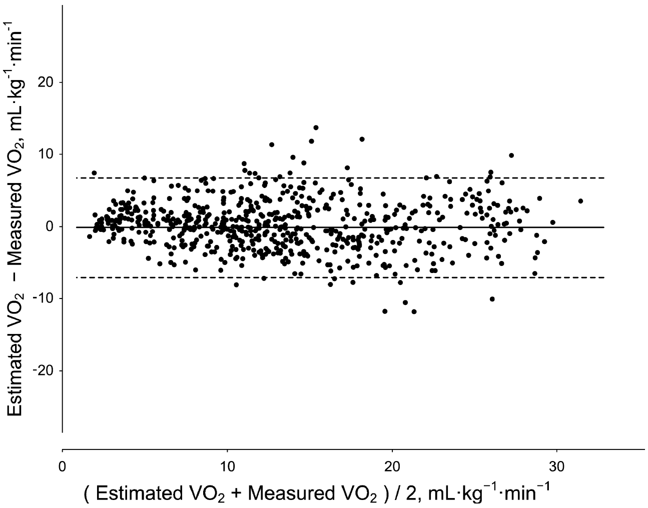

FIGURE 4—Bland–Altman analysis showing the precision of estimating oxygen consumption rate ($\dot{V}O_2$) by equation 4. The *solid* and *dashed lines* indicate the mean error and 95% confidence intervals, respectively.

Figure 3, and the agreement between them was assessed using Bland–Altman analysis (4) in Figure 4.

RESULTS

Treadmill study. During graded walking, when HR and $\dot{V}O_2$ for the second half of the final minute in each 3-min trial was compared with those for the first half, $\dot{V}O_2$ and HR both deviated by less than 2% with no significant differences, indicating that they had reached a steady state. Table 3 shows the averaged walking speed, VM, HR, and $\dot{V}O_2$ for the last 1 min of each trial with the number of subjects who completed whole 3-min trials.

Figure 2 shows the relationship between VM and $\dot{V}O_2$ during walking on each incline of the treadmill with regression equations. As shown in the panels of Figure 2, the regression coefficient increased significantly as the incline of the treadmill increased ($P < 0.001$, between any inclines), whereas it decreased significantly for the incline of –5% ($P < 0.001$, vs 0%) and continued to decrease slightly but significantly as the downhill inclines further decreased to –10% and –15% ($P < 0.05$ and $P < 0.001$, respectively, vs –5%).

The regression equation to estimate $\dot{V}O_2$ during walking on the pooled data was determined as

$$\dot{V}O_2 = 0.044\mathrm{VM} + 1.365H_u + 0.553H_d \ (r = 0.93,\ P < 0.001). \quad [4]$$

Because the variance inflation factors were 1.01 for VM versus H_u and 1.09 for VM versus H_d, we confirmed that no multicollinearity was present, and variables were independent of each other. Moreover, we performed the same analyses on each subject, after confirming significant correlation between $\dot{V}O_2$ and other variables ($P < 0.05$), and determined $k_1 = 0.046 \pm 0.008$(SD), $k_2 = 1.328 \pm 0.182$, and $k_3 = 0.590 \pm 0.164$ for all subjects, which were almost identical to those of equation 4, respectively. Therefore, we used equation 4 for the subsequent field validation study.

TABLE 3. Walking speed, VM, $\dot{V}O_2$, and HR during walking on various inclines in the treadmill study.

	−15%	−10%	−5%	0%	+5%	+10%	+15%
Rest							
Speed (km·h^{-1})	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
VM (G)	13 ± 1	13 ± 1	13 ± 1	13 ± 1	13 ± 1	12 ± 1	13 ± 1
$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})	3.7 ± 0.1	3.8 ± 0.1	3.6 ± 0.1	3.6 ± 0.1	3.5 ± 0.2	3.5 ± 0.1	3.7 ± 0.1
HR (beats·min^{-1})	75 ± 2	74 ± 2	74 ± 2	75 ± 2	72 ± 2	70 ± 2	71 ± 2
n	39	40	41	41	41	39	38
Slow							
Speed (km·h^{-1})	2.7 ± 0.1	2.9 ± 0.0	3.0 ± 0.0	3.0 ± 0.0	3.1 ± 0.1	2.8 ± 0.1	2.5 ± 0.1
VM (G)	159 ± 7	157 ± 5	154 ± 4	151 ± 4	154 ± 4	144 ± 4	137 ± 4
$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})	8.2 ± 0.3	8.6 ± 0.4	8.6 ± 0.3	11.1 ± 0.3	13.2 ± 0.2	15.6 ± 0.4	17.6 ± 0.5
HR (beats·min^{-1})	84 ± 2	82 ± 2	84 ± 2	92 ± 2	95 ± 2	101 ± 2	107 ± 2
n	39	40	41	41	41	39	38
Moderate							
Speed (km·h^{-1})	3.7 ± 0.1	3.9 ± 0.0	4.0 ± 0.0	4.0 ± 0.1	4.2 ± 0.1	3.8 ± 0.1	3.3 ± 0.1
VM (G)	236 ± 9	220 ± 7	213 ± 6	198 ± 5	203 ± 5	190 ± 6	178 ± 6
$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})	10.8 ± 0.4	9.3 ± 0.4	9.9 ± 0.4	12.9 ± 0.4	16.5 ± 0.3	20.0 ± 0.4	22.3 ± 0.6
HR (beats·min^{-1})	89 ± 3	85 ± 3	88 ± 2	98 ± 2	106 ± 2	116 ± 2	123 ± 2
n	39	40	41	41	41	39	38
Fast							
Speed (km·h^{-1})	4.6 ± 0.1	4.8 ± 0.0	5.0 ± 0.0	5.0 ± 0.1	5.2 ± 0.1	4.7 ± 0.1	4.1 ± 0.1
VM (G)	322 ± 10	293 ± 8	284 ± 7	267 ± 7	272 ± 7	253 ± 8	223 ± 8
$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})	10.8 ± 0.5	10.5 ± 0.4	12.1 ± 0.5	15.9 ± 0.4	21.2 ± 0.5	24.8 ± 0.5	27.2 ± 0.7
HR (beats·min^{-1})	95 ± 3	91 ± 3	97 ± 2	108 ± 2	120 ± 2	133 ± 2	141 ± 2
n	39	40	41	41	40	39	37
Fastest							
Speed (km·h^{-1})	NA	NA	NA	5.9 ± 0.1	NA	NA	NA
VM (G)	NA	NA	NA	343 ± 9	NA	NA	NA
$\dot{V}O_2$ (mL·kg^{-1}·min^{-1})	NA	NA	NA	20.0 ± 0.5	NA	NA	NA
HR (beats·min^{-1})	NA	NA	NA	118 ± 2	NA	NA	NA
n	NA	NA	NA	31	NA	NA	NA

Percent values indicate inclines of the treadmill. Values are presented as means ± SE.
n, number of subject; NA, not applicable.

Field validation study. As shown in Figure 3, we found that the estimated $\dot{V}O_2$ was significantly correlated with the measured $\dot{V}O_2$ on the data pooled from the 11 subjects ($r = 0.879$, $P < 0.001$) with a regression equation of $y = 0.969x$, and the mean difference was -0.20 mL·kg^{-1}·min^{-1} and 95% prediction limits were ±6.95 mL·kg^{-1}·min^{-1} over the range of 2.0–33.0 mL·kg^{-1}·min^{-1} in the Bland–Altman analysis (Fig. 4).

DISCUSSION

In the present study, we proposed a new algorithm to estimate $\dot{V}O_2$ during walking on various inclines with a triaxial accelerometer and barometer more precisely than previously reported by accelerometry alone (6,14,20). Moreover, we confirmed the suitability of this algorithm in the field by developing a portable device mounted with a triaxial accelerometer, a barometer, and a computer program to estimate $\dot{V}O_2$.

Improvement in the estimation of $\dot{V}O_2$ after correction for altitude changes. Terrier et al. (20) examined the accuracy of accelerometry to predict energy expenditure during incline walking and reported results similar to those shown in Figure 2. More recently, Campbell et al. (5) compared $\dot{V}O_2$ by two methods while subjects repeated a 5-min exercise of ascending and descending a flight of 17 stairs and a 21% (12°) incline 32 m long and reported that the $\dot{V}O_2$ by accelerometry was 33% lower than that by respiratory gas analysis during the stair climbing but only 2% higher during the incline walking. However, it should be remembered that the $\dot{V}O_2$ was obtained as a net value after cancellation of underestimation and overestimation by accelerometry during uphill and downhill walking, respectively. Thus, the estimation by accelerometry was largely biased during incline walking and sometimes masked in the field.

To address these problems, Aminian et al. (2) estimated the speed and the incline from accelerations at the lower back and the heel during uphill and downhill walking from a computer program fitted for individuals. However, the program needed to be determined by having subjects walk on various inclines of a treadmill before the measurements in the field. Also, it might need to be revised if walking form were to change as training advanced. Recently, Perrin et al. (18) suggested that the walking speed in the field can be estimated more precisely than the accelerations alone by measuring altitude variation using a satellite positioning system. However, it may prove difficult to install such complex instrumentation in a portable device broadly used for individuals in the field. Further, they did not provide any algorithms to convert the speed and the incline to $\dot{V}O_2$ during walking.

In the present study, we successfully determined the regression equation to estimate $\dot{V}O_2$ during walking on inclines with a high precision, suggesting that the biased energy expenditure during incline walking was completely corrected for by the algorithm. The 95% prediction limits between measured and estimated $\dot{V}O_2$ in the field validation study were ±6.95 mL·kg^{-1}·min^{-1}, equivalent to $-1.0 \pm 33.5 \times 10^{-3}$ kcal·kg^{-1}·min^{-1} assuming that the respiratory quotient is 0.82.

Different gain of effects by altitude change on $\dot{V}O_2$ between downhill and uphill walking. k_3 was less than half of k_2 as shown in equation 4; therefore, for a given change in altitude, change in $\dot{V}O_2$ is lower in downhill than in uphill walking, confirming that the mechanisms for energy expenditure during downhill walking are different from those for uphill walking. Minetti et al. (12) measured energy expenditure for "positive" work related to the position and speed of the body center during walking on inclines and suggested that almost 100% of total energy expenditure for work was expended for "positive" work during walking on a +15% incline, decreasing to 50% on the 0% incline, and almost 0% below –5%. Thus, during downhill walking, the energy is expended for "negative" work to buffer the impact of the fall of the body due to gravity.

Long ago, Abbott et al. (1) measured $\dot{V}O_2$ during positive and negative work using cycle ergometers and suggested that $\dot{V}O_2$ for negative work was 20%–40% of that for the positive work at a given mechanical workload. More recently, Perrey et al. (17) assessed a similar issue and suggested that $\dot{V}O_2$ during eccentric cycling; negative work, was ~20% of that of concentric cycling; positive work. Thus, the energy expenditure for negative work is lower than that for positive work, which might be responsible for the blunted effects of altitude change on $\dot{V}O_2$ during downhill walking.

Regarding the significantly higher coefficient of variation in k_3 than in k_2, Terrier et al. (20) measured energy expenditure during walking on a treadmill varying from +15% to –15% incline, and found that the energy expenditure at a given speed decreased in proportion to the incline above –5%, but below that level the decrease rate was markedly blunted, reached the minimal level at –10%, and almost remained unchanged at –15% as reconfirmed by us in Figure 2. Thus, the higher coefficient of variation in k_3 during downhill walking might occur because energy expenditure for negative work was almost constant despite the steeper downhill incline whereas that for positive work during uphill walking increased as the uphill incline increased. Moreover, this might be partially caused by interindividual differences such as in the knee movement during downhill walking or the thigh muscle strength.

Limitations of the device. The device developed in this study is applicable to estimate additional $\dot{V}O_2$ required for walking at 2.0–7.0 km·h^{-1} on inclines of ±15% in excess of rest for middle-aged and older people. Also, because altitude change was determined every 1 min, more rapid changes in altitude during walking were ignored. Moreover, the influence of atmospheric temperature on calculation of altitude from barometric pressure (equation 3) was also ignored.

In conclusion, the biased estimation of $\dot{V}O_2$ by accelerometry alone during walking on an incline was corrected for by putting altitude change measured with a barometer into the algorithm developed in the present study.

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