Automatic classification of ambulatory movements and evaluation of energy consumptions utilizing accelerometers and a barometer

Article *in* Microsystem Technologies · August 2005

DOI: 10.1007/s00542-005-0502-z

6 authors, including:

Yasuaki Ohtaki
Kanagawa Institute of Technology
89 PUBLICATIONS **237** CITATIONS

SEE PROFILE

Koichi Sagawa
Hirosaki University
75 PUBLICATIONS **396** CITATIONS

SEE PROFILE

Ryoichi Nagatomi
Tohoku University
279 PUBLICATIONS **2,935** CITATIONS

SEE PROFILE

Hikaru Inooka
Tohoku University
180 PUBLICATIONS **1,902** CITATIONS

SEE PROFILE

Microsyst Technol (2005) 11: 1034–1040
DOI 10.1007/s00542-005-0502-z

TECHNICAL PAPER

Yasuaki Ohtaki · Mitsutoshi Susumago
Akihiro Suzuki · Koichi Sagawa · Ryoichi Nagatomi
Hikaru Inooka

Automatic classification of ambulatory movements and evaluation of energy consumptions utilizing accelerometers and a barometer

Received: 22 July 2003 / Accepted: 6 November 2003 / Published online: 10 August 2005

Abstract This paper describes a method to evaluate daily physical activity by means of a portable device that determines the type of physical activity based on accelerometers and a barometer. Energy consumption of a given type of physical activity was calculated according to relative metabolic ratio (RMR) of each physical activity type that reflects exercise intensity of activities. Special attention was paid to classification algorithms for activity typing that identify detailed ambulatory movements considering vertical movements, such as stair/slope climbing or use of elevators. A portable measurement device with accelerometers and a barometer, and a Kalman filter was designed to detect the features of vertical movements. Furthermore, walking speed was calculated by an equation which estimates the walking speed as a function of signal energy of vertical body acceleration during walking. To confirm the usefulness of the method, preliminary experiments were performed with healthy young and elderly subjects. The portable device was attached to the waist. A standard accelerometer based calorie counter was also attached for comparison. Experimental results showed that the proposed method feasibly classified the type of ambulatory physical activities; level walking, stair going up and down and elevator use. It was suggested that the consideration of vertical movements made a significant improvement in the estimation of energy consumptions, and the proposed method provides better estimation of physical activity compared to the conventional calorie counter.

Y. Ohtaki (✉) · H. Inooka
Graduate School of Engineering, Tohoku University,
6-6-04 Aoba, Aoba-ku, Sendai 980-8579, Japan
E-mail: ohtaki@niche.tohoku.ac.jp
Tel.: +81-22-7953157
Fax: +81-22-7953157

M. Susumago
Yokogawa Electric Corporation, 9-32 Nakacho 2-chome,
Musashino, Tokyo 180-8750, Japan

A. Suzuki
Instruments Technology Research Co. Ltd., 2-1-40 Takamori,
Izumi-ku, Sendai 981-3203, Japan

K. Sagawa
Faculty of Science and Technology, Hirosaki University,
3 Bunkyo-cho, Hirosaki, Aomori 036-8561, Japan

R. Nagatomi
Graduate School of Medicine, Tohuku University,
2-1 Seiryou, Aoba-ku, Sendai 980-8574, Japan

1 Introduction

Physical activity is a determining factor of quality of life. A practical and reliable method to investigate individual's daily physical activity allows better assessment such as of outcomes of medical interventions. Currently, the amount of energy consumption due to daily physical activity is widely accepted as an important factor in the prevention of obesity, diabetes, hyperlipidemia, cardiovascular disease, and muscle wasting in the aged people. Information such as intensity of exercise, types of activities is also necessary to appropriately formulate safe and beneficial exercise program on individual basis. Ambulatory movement is the most accessible type of exercise easy to perform that does not require any special equipments. Therefore, a reliable assessment of ambulatory movements in daily life, such as walking, climbing stairs or slopes up and down, is essential for exercise prescription in the clinics as well as in health promotion programs.

Conventionally, clinicians simply recorded patients' recall of daily exercise to evaluate energy expenditure of patients. A variety of methods have also been used to quantify daily energy expenditure in a more precise manner, by means of heart rate monitoring, oxygen uptake measurement or doubly labeled water. However, these methods are either unreliable, cumbersome or impractical in recording daily energy expenditure of free living people. In order to overcome these problems, various advanced small calorie counters have been developed utilizing an accelerometer or an angular velocity sensor attached on the waist, wrist or ankle.

Accelerometers are preferable to detect frequency and intensity of vibrational human motion (Morris et al. 1973; Bouten et al. 1997). Many studies have demonstrated the usefulness of accelerometry for the evaluation of physical activity, mostly focusing on the detection of level walking or active/rest discrimination (Tamura et al. 1997; Nakahara et al. 1999; Aminian et al. 1999; Mathie et al. 2002). However, with regard to vertical movements such as stair climbing, evaluation of energy consumption has been still insufficient even though stair climbing requires more than twice the energy of level walking. This is because of difficulties in the detection of vertical movement. As for the detection of vertical position shift, DGPS as an infrastructure-dependent positioning technology made better measurement of vertical positioning. However, it has serious problems of coarse time resolution and limited availability of the satellite service. Walking speed also contributes to energy consumption, though it is still difficult to estimate accurately under unconstrained ambulatory conditions from acceleration data. New methods have been proposed utilizing a neural network or a mechanical biped model that needs tuning each time (Aminian et al. 1995, 2002; Miyazaki et al. 1997). Uses of multiple wearable vital sensors still involves some restrictions and discomfort that may interfere with natural and spontaneous daily physical activity.

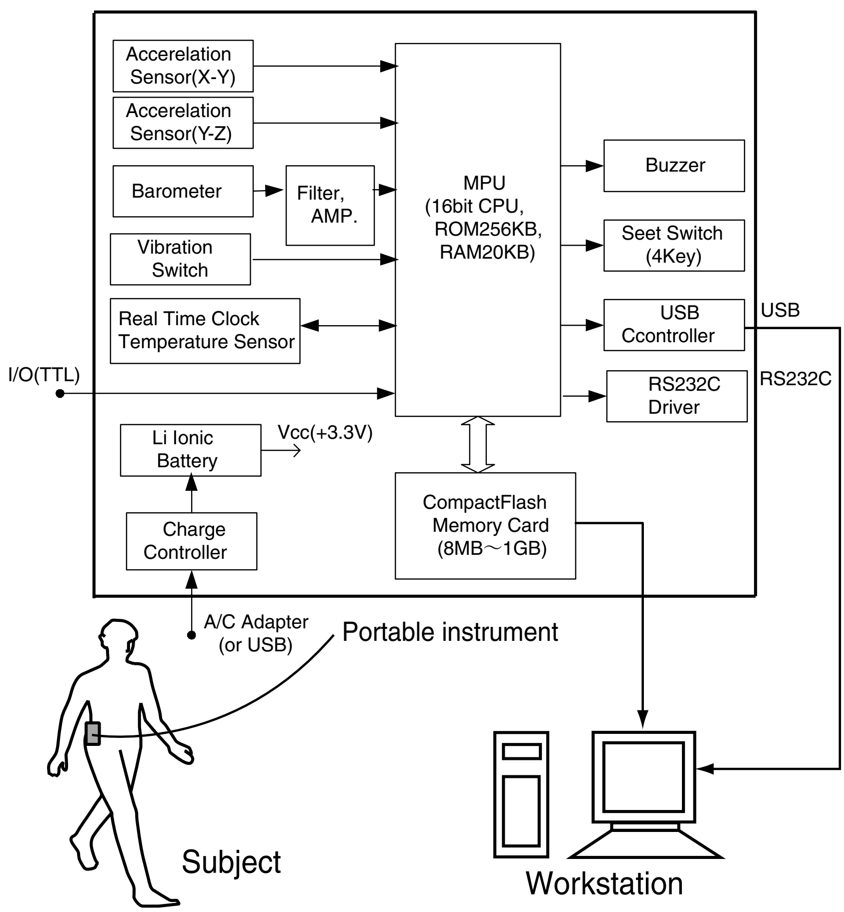
Main objective of this study was to present a method to quantify energy consumption of detailed ambulatory movements, both indoors and outdoors in daily life, by use of a portable measurement device employing accelerometers and a barometer. Special attention was paid to advanced classification algorithms and walking speed estimation, which was robust to measurement conditions, individual differences, and aging effect. Potential usefulness of the proposed method was investigated by comparing the new method with the conventional accelerometer based calorie counter in the experimental study.

2 Method

2.1 Portable measurement device

We developed a portable device consisted of monolithic IC accelerometers (AnalogDevices, ADXL202E, ±2 [G]) with 16-bit duty cycle converter, a packaged silicon piezoresistive pressure sensor (Fujikura, X3AM-115KPASR), Li-Ionic batteries, micro processor units and CompactFlash card, as shown in Figure 1. This equipment (Instruments Technology Research, Intelli-

Fig. 1 Architecture of the portable measurement device



gent Calorie Counter: ICC) was small (100×55×18.5 [mm]) and light enough to carry without any restriction. Sampling frequency was selectable from 10, 33.3, 100 [Hz]. Data was downloaded via USB, and processed offline by a workstation. The equipment was designed to be attached on the waist as shown in Figure 2. Although the equipment provided three-dimensional acceleration, vertical acceleration and air pressure data were applied to the classification method of ambulatory movement typing.

2.2 Estimation of energy expenditure

Energy expenditure is calculated as shown in Equation 1. Total energy consumption E is the summation of energy consumed by exercise E_w and individual's basic metabolism E_b. The relative metabolic rate (RMR) represents the ratio of energy expenditure that is required for the exercise and one's basal metabolism. The basal metabolic rate (BMR) is the number of calories burned in a day while lying down, which depends on one's age or gender. The notation t and w represent the exercise time length and the body weight respectively. It should be noted that the type of exercise and intensity are determinant factors of RMR, as shown in Table 1 ("Guidelines for graded exercise testing and exercise prescription" published by American College of Sports Medicine. 1986; Ainsworth et al. 1993). Therefore, a precise evaluation of energy expenditure in daily life with the new device requires detailed classification of ambulatory movements with stair/slope-climbing activity taken into consideration.

$$
\begin{aligned}
E &= E_w + E_b \\
E_w &= RMR \times BMR \times t \times w
\end{aligned}
\quad (1)
$$

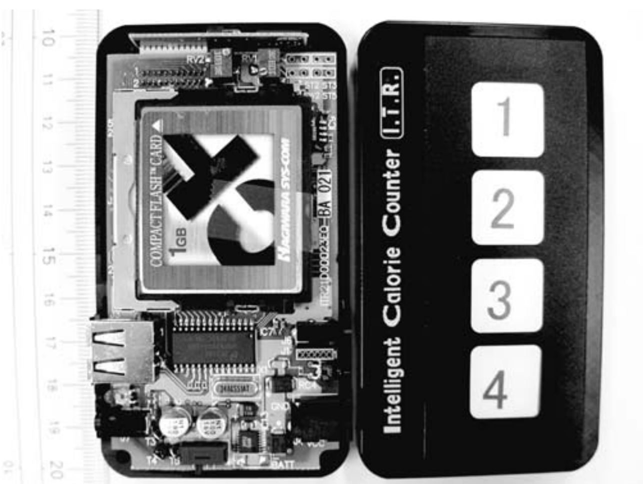


Fig. 2 Photo of the portable measurement device: Intelligent Calorie Counter (ICC)

Table 1 RMR (Relative Metabolic Rate)

Type of Motion	RMR
Rest(Standing)	0.4
Rest(Sitting)	0.0~0.2
Rest(Lie Down)	0.0
-Walking Speed-	
50 m/min	1.5
60 m/min	1.9
70 m/min	2.4
80 m/min	3.2
90 m/min	4.0
100 m/min	5.0
110 m/min	6.4
120 m/min	8.5
-Slope Walking-	
-9 %	1.3
-5 %	1.7
5 %	3.8
10 %	5.4
15 %	7.2
20 %	9.4
-Stair-	
Up	10.0
Down	2.5

2.3 Detection of walking phase

The body acceleration reflects characteristics of the biped locomotion. The walking periodicity appears as a frequency peek f_p in a spectrum, and the intensity of movement corresponds to amplitudes and the signal energy of acceleration, as shown in Figure 3. Therefore,

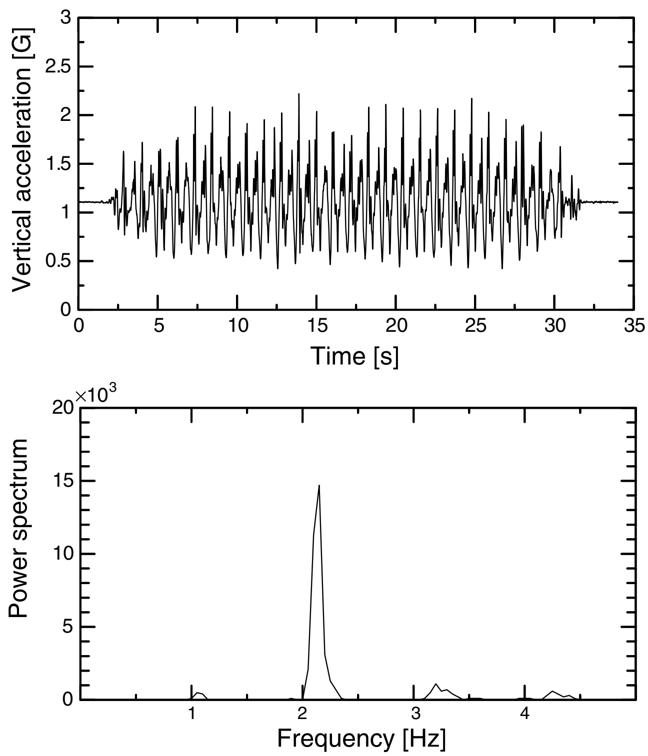


Fig. 3 Vertical acceleration and power spectrum during walking

walking phases were defined by the acceleration as a condition with a variance S over 0.02 [G] and frequency peak inside f_p 1–3 [Hz] in the spectrum.

2.4 Estimation of walking speed

Furthermore, a method of walking speed estimation was developed. It is known that natural human gait has a clear relationship between step length and cadence. These factors reflect frequency and intensity of the vertical trunk vibration during walking (McMahon 1984). Therefore, we focused on the relationship between signal energy and natural walking speed. The signal energy in the frequency bandwidth 1–3 [Hz] was considered as a determinant of one's natural walking speed. The relationship between signal energy and natural walking speed was formulated from walking test results of 199 young (Age: 25.0 ± 1.63) and elderly (Age: 75.2 ± 7.83) subjects. From the result of the experiment, an approximate expression as a clear logarithmic relationship was found among the signal energy and the walking speed, as shown in Figure 4. Estimation equation of walking speed was thus formulated as Equation 2. The notation x represents the signal energy of 1–3 [Hz] frequency bandwidth of vertical acceleration. The notation y represent the walking speed standardized by subject's height. This method does not require any personal template of biped model, pre-investigation of step length, but applicable to walking speed estimation of elderly people.

$$y = 0.1722 \ln(x) - 0.3346 \tag{2}$$

2.5 Detection of vertical movement

In order to classify ambulatory including vertical position shift, a practical methods was developed to detect slight altitude changes by use of a barometer. Direct measurement of the air pressure or its differential hardly gives precise altitudes change, because of the effect of weather conditions, artifacts, and high frequency measurement noise. Weather conditions sometimes cause larger air pressure changes than that of the vertical altitude change caused by one's motion. However, the change in the atmospheric pressure due to weather changes appears to be much slower than that caused by one's motion. On the other hand, air pressure differentials practically indicate vertical position shifts. It is also beneficial that the measurement of air pressure differentials provides wider dynamic measurement range as compared to absolute air pressure measurement. Considering the above points, a Kalman filter with following characteristics was designed to eliminate effects of such disturbances and to get optimal estimation of the air pressure differential.

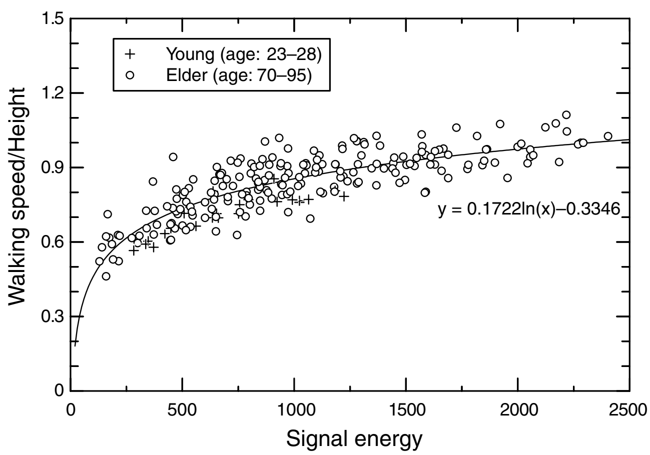


Fig. 4 Relationship between walking speeds standardized with height and the signal energy of acceleration

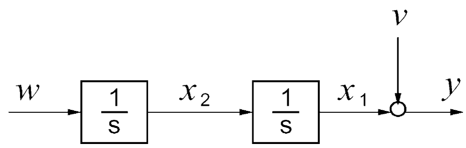


Fig. 5 The model of air pressure measurement

To construct the filter, a model of the air pressure measurement system was proposed as shown in Figure 5 (Sagawa et al. 1998). The notation x_1 and x_2 represent an air pressure and its differential of the state variable $\mathbf{x}$ respectively. The notation v is the sensor noise and y is the output of the barometer. The notation w represents a virtual signal that corresponds to a dynamic error between a signal generation model and the actual air pressure. An optimal filter to estimate a state variable $\mathbf{x} = [x_1\ x_2]^T$ using the sensor output y will be written by a Kalman filter as follow.

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{K}(\mathbf{y} - \mathbf{C}\hat{\mathbf{x}}) \tag{3}$$

The equation provides a transfer function $G_k(s)$ from the sensor output y to the optimal estimation of the air pressure differential $\hat{x}_2$.

$$G_k(s) = \frac{{\omega_k}^2 s}{s^2 + 2\zeta_k \omega_k s + \omega_k^2} \tag{4}$$

where w_k and ζ_k are natural frequency and damping ratio, respectively. Moreover, an amplifier and an low pass filter with a cut-off frequency of 10 [Hz] is applied to the output signal. The bode diagram of the constructed filter is shown in Figure 6. The filter works as differentiation in the frequency range lower than 0.3 [Hz].

A value of air pressure differential corresponds to a direction and speed of the vertical movements. Therefore, types of vertical motion or kinds of transporter can be identified according to the value of air pressure differential combined with the result of walking phase detection.

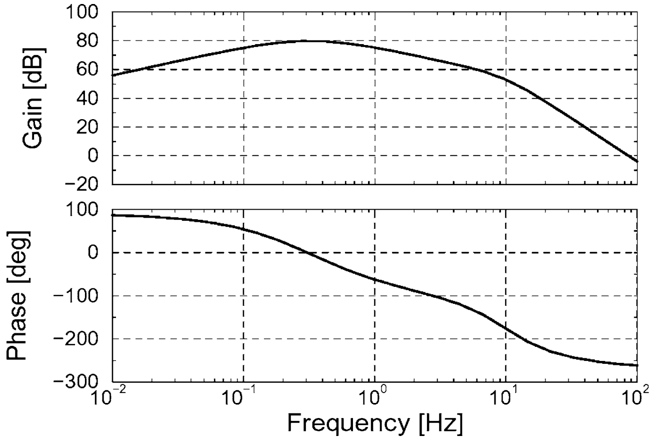


Fig. 6 Bode diagram of the filter

2.6 Classification algorithm

There were four steps in the classification algorithm. The first step was the separation of ambulatory and resting states. The second step was the detection of vertical position shift and detailed identification of up/down movements. The third step was the estimation of walking speeds and slope inclination to evaluate the intensity of the movement. Threshold and clustering approach provided classification of level walking, climbing up/down the stair/slope, going up/down in an elevator, and rest (Static). The threshold value and the classification condition were described as Equation 5 – Equation 10. The value of air pressure differentials $dA_p = 1$ [Pa] correspond to vertical position shift of 8.49 [cm]. The threshold values were determined considering reported characteristics of human walking and the Japanese guideline of elevator design. The threshold values were experimentally adjusted and verified by the preliminary investigation of six kinds of elevators (Lifting speed: 58.9 - 101.5 [m/min]) and four kinds of stairs (Inclination pitch: 3.5 - 30.0 [deg.]). In the classification algorithm, short term movements less than 3 second was negligible to assess main series of ambulatory movements.

$$\left\{ \text{Level walking} \left| \begin{array}{l} S^2 \geq 0.02\ [G],\ 1 < f_p < 3\ [Hz] \\ -1.86 < dA_p < 1.86\ [Pa/s] \end{array} \right. \right\} \tag{5}$$

$$\left\{ \begin{array}{l} \text{Stair Slope} \\ \text{Going Up} \end{array} \left| \begin{array}{l} S^2 \geq 0.02\ [G],\ 1 < f_p < 3\ [Hz] \\ dA_p > 1.86\ [Pa/s] \end{array} \right. \right\} \tag{6}$$

$$\left\{ \begin{array}{l} \text{Stair/Slope} \\ \text{Going Down} \end{array} \left| \begin{array}{l} S^2 \geq 0.02\ [G],\ 1 < f_p < 3\ [Hz] \\ dA_p < -1.86\ [Pa/s] \end{array} \right. \right\} \tag{7}$$

$$\left\{ \begin{array}{l} \text{Elevator} \\ \text{Going Up} \end{array} \left| \begin{array}{l} 0 \leq S^2 \leq 0.02\ [G] \\ dA_p > 8.64\ [Pa/s] \end{array} \right. \right\} \tag{8}$$

$$\left\{ \begin{array}{l} \text{Elevator} \\ \text{Going Down} \end{array} \left| \begin{array}{l} 0 \leq S^2 \leq 0.02\ [G] \\ dA_p < -8.64\ [Pa/s] \end{array} \right. \right\} \tag{9}$$

$$\left\{ \text{Rest (Static)} \left| \begin{array}{l} 0 \leq S^2 \leq 0.02\ [G] \\ -8.64 < dA_p < 8.64\ [Pa/s] \end{array} \right. \right\} \tag{10}$$

3 Experiment

Two kinds of preliminary experiments were performed with healthy young subjects. All subjects gave signed informed consent. Subjects wore their own shoes. The measurement data was processed offline by the proposed classification algorithm.

First experiment (Experiment 1) was demonstrated to show the usefulness of the method to identify and classify details of ambulatory movements. Subjects were thirteen young volunteers (Age: 23.9 ± 2.02). The portable device ICC was attached on the waist of subject. Sampling frequency was 100 [Hz]. Subjects were instructed to move in the sequence of "static standing, going down in an elevator, walking through level corridor, climbing up stairs, walking climbing down stairs walking, and going up in an elevator".

The second experiment (Experiment 2) was performed to investigate whether the detailed classification provides significant differences in the evaluation of energy consumption as compared with conventional accelerometry. Subjects were five young volunteers (Age: 23.2 ± 2.39). In addition to ICC, accelerometer based calorie counter (Kenz, Lifecorder) as a standard of conventional method was attached on the other side of the waist. Sampling frequency was 100 [Hz]. The accelerometer based calorie counter provides data of exercise intensity every four seconds. Subjects were instructed to walk along a course three times in the sequence of "level walking, climbing down stairs, walking, climbing up stairs, and walking". Walking speed was changed every round in the order of "normal, slow, and fast" on their own decision.

The third experiment (Experiment 3) was performed to assess the validity of the method in a community environment. Two elderly subjects (Age: 71 and 82) volunteered for a two day monitoring of physical activity in their personal lives. They carried ICC for 16 hours each day. To enable long-term recordings, sampling frequency was reduced to 33.3 [Hz]. Types of ambulatory movement in their daily life were investigated.

4 Result

Typical result of Experiment 1 was shown in Figure 7 illustrating vertical accelerations (top), air pressure differentials (middle) and classification results of the movements (bottom). The value of air pressure differential changed according to the direction and the speed of vertical movements. All types of ambulatory movements were successfully classified. Indeed, a few steps in and out of the elevator cage was detectable just before and after the use of elevator. Such short walking less than three second were neglected in the classification process. The series of ambulatory movements could be accurately classified in all the subjects and the trials. The algorithm made about 1.5 second delay for classification, which is negligible in the evaluation of energy expenditure. On the other hand, large ripples were observed in the air pressure differential, probably caused by the pre-amp of the barometer. This ripple made a limitation in the classification method. When climbing up/down stairs/slopes less than 10 [deg] angle, frequent miss classification was observed because of less variation of air pressure differential than that of the ripple.

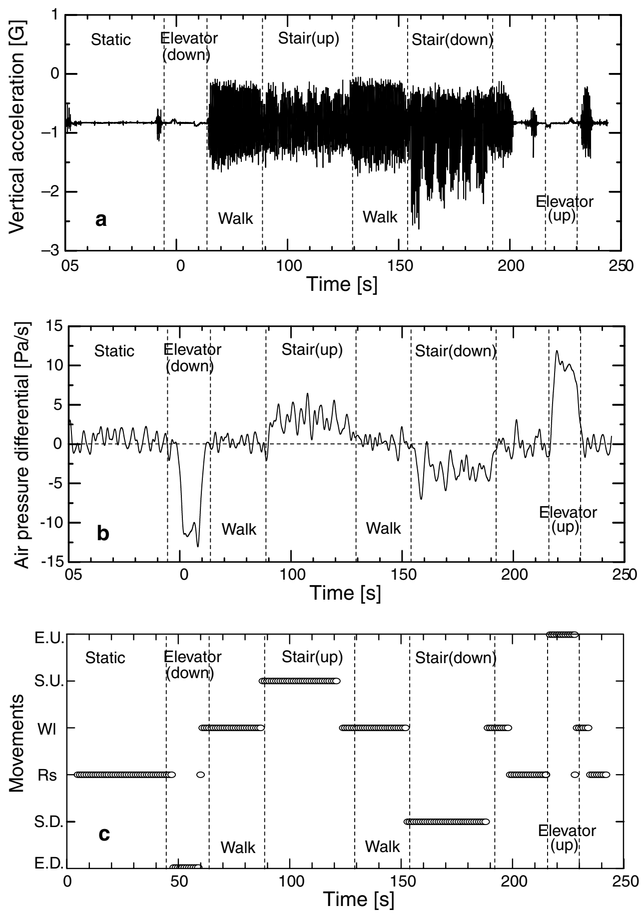


Fig. 7 Typical waveform of vertical accelerations (top), air pressure differentials (middle) as measured, and classification results of the ambulatory movements (bottom). The notation E.U., S.U., Wl, Rs, S.D., E.D. indicate 'Elevator going up', 'Stair going up', 'Level walking', 'Rest(static)', 'Stair going down', 'Elevator going down' respectively

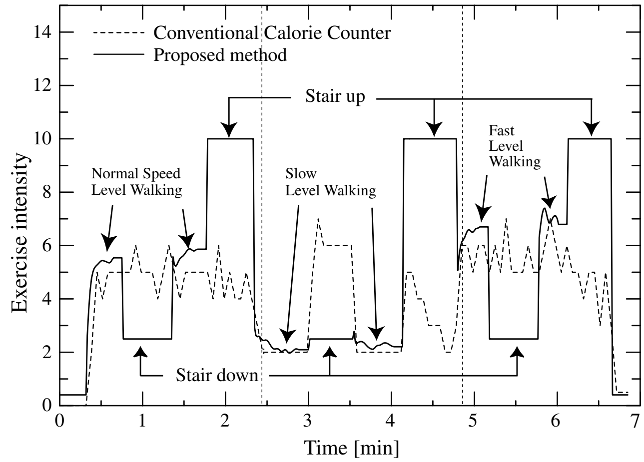


Fig. 8 Exercise intensities estimated by the proposed method during level walking in various speed and stair up/down, comparing with the results of conventional accelerometer based calorie counter

The result of Experiment 2 was shown in Figure 8 illustrating exercise intensity estimated by ICC compared with the result of standard calorie counter. ICC provided the exercise intensity as RMR. Note that ICC successfully evaluated exercise intensity of the vertical movements whereas the conventional accelerometer based calorie counter ignored them. This result suggested that the conventional evaluation of stair climbing upwards was underestimated, and stair climbing downwards was overestimated. As illustrated in Figure 8, during the second round when subjects moved slower, the conventional accelerometer overestimated stair climbing downwards. This can be explained by the fact that conventional accelerometer calculates energy consumption simply according to the intensity of acceleration. Speed

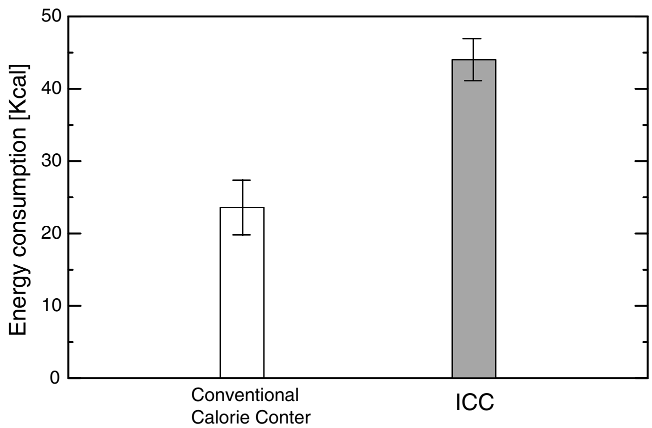


Fig. 9 Comparison of estimated total energy consumption by the proposed method and the conventioanal accelerometer based calorie counter

Table 2 Distribution of daylong physical activity

Subject No.		Level walk [min] (RMR < 7)	Stair up/down [min]
1	1st day	101.95	9.15
	2nd day	88.68	7.12
2	1st day	55.42	1.67
	2nd day	53.27	0.98

of level waking was also evaluated correctly in a good agreement with the result of the conventional method. Figure 9 shows the comparison of the total amount of expenditure during the trial. The energy consumption estimated by ICC was larger than the conventional method. It was suggested that the consideration of vertical ambulatory movements may provide a significant improvement in the evaluation of energy expenditure in daily activities. However, the reliability of the estimated values is still uncertain. The measurement of the oxygen uptake should be performed to confirm the reliability of the estimation. The stepping speed of stair climbing was not addressed in our method. This is because RMR table has not addressed the intensity of stair climbing speed sufficiently, even though the calculation of stair walking speed would not be difficult.

The result of Experiment 3 was shown in Table 2. The proposed method successfully illustrates the classification of ambulatory movements in daily lives. This information may be helpful in formulating more appropriate and safer exercise program on individual basis. This method should be extended to cover other types of movements in order to realize wider application and a more precise assessment of daily physical activity. Further clinical and community-based studies with a larger number of subjects are our future studies.

5 Conclusion

In this article, an alternative method to evaluate energy expenditure of ambulatory movements was described. A small portable device utilizing accelerometers and a barometer was developed, which detects features of ambulatory movements including vertical position shifts. The classification method based on a frequency analysis of body acceleration and data processing of air pressure variation provided identification and classification of one's ambulatory movements without significant limitations and restrictions. Furthermore, walking speed was estimated from the signal energy of the acceleration. Experimental results have shown that the proposed method is able to effectively classify and evaluate level walking, stair/slope climbing, elevator use, and walking speed. The proposed method provides better estimation of energy expenditure and exercise intensity as compared to conventional accelerometer based calorie counters.

This device is feasible for community-based studies. Further application of the present technique may be helpful in the health promotion of both young and elderly, and in the management of obese, diabetic, hyperlipidemic and cardiac patients. Efforts are being directed to make the device smaller and allow data collection for longer time periods. Implementation of real-time processing firmware and encapsulation of the hardware are our future studies.

Acknowledgements We are grateful to Dr. K. Fujita, Dr. I. Tsuji at Graduate School of Medicine, Tohoku University, and Miyagi Physical Therapist Association for their cooperation in our study. This research is grant aided by Japanese Ministry of Education, Culture, Sports, Science and Technology; the Knowledge Cluster Project "Sendai Cyber Forest".

References

Ainsworth BE, Haskell WL, Leon AS, Jacobs DR Jr, Montoye HJ, Sallis JF, Paffenbarger RS Jr (1993) Compedium of physical activities: classification of energy cost of human physical activities. Medicine and Science in Sports and Exercise 25(1):71–80

American College of Sports Medicine (1986) Guidelines for graded exercise testing and exercise prescription, 3rd edn. Lea and Febiger, Philadelphia

Aminian K, Robert Ph, Jequier E, Schutz Y (1995) Estimation of speed and incline of walking using newral network. Transaction of Instrumentation and Measurement 44(3):743–746

Aminian K, Robert P, Buchser EE, Rutschmann B, Hayoz D, Depairon M (1999) Physical activity monitoring based on accelerometry. Medical and Biological Engineering and Computing 37:304–308

Aminian K, Najafi B, Bula C, Leyvraz PF, Robert Ph (2002) Spatio-temporal parameters of gait measured by an ambulatory system using miniature gyroscopes. Journal of Biomechanics 35(5):689–699

Bouten CVC, Koekkoek KTM, Verduin M, Kodde R, Janssen JD (1997) A triaxial accelerometer and portable data processing unit for the assessment of daily physical activity. IEEE Transactions on Biomedical Engineering 44(3):136–147

Mathie MJ, Lovell NH, Coster CF, Celler BG (2002) Determining activity using a triaxial accelerometer. In: Proceedings of the second joint EMBS/BMES conference, 2481–2482

McMahon TA (1984) Mechanics of Locomotion. The International Journal of Robotics Research 3(2):4–28

Miyazaki S (1997) Long-term unrestrained measurement of stride length and walking velocity utilizing a piezoelectric gyroscope. IEEE Transactions on Biomedical Engineering 44(8):1701–1707

Morris JRW (1973) Accelerometry–a technique for the measurement of human body movements. Journal of Biomechanics 6:729–736

Nakahara AK, Sabelman EE, Jaffe DL (1999) Development of a second generation wearable accelerometric motion analysis system. Proceedings of the first joint EMBS/BMES conference, 630

Sagawa K, Ina A, Ishihara T, Inooka H (1998) Classification of human moving patterns using air pressure and acceleration. In: Proceedings of the 24th Annual Conference of the IEEE Industrial Electronics Society (IECON'98) 2:1214–1219

Tamura T, Fujimoto T, Sakaki H, Higashi Y, Yoshida T, Togawa T (1997) A Solid-State Ambulatory Physical Activity Monitor and Its Application to Measuring Daily Activity of the Elderly C. Journal of Medical Engineering and Technology 21:96–105