Estimation of Energy Expenditure during Sedentary Work with Upper Limb Movement

Kunio TSURUMI, Toru ITANI, Norihide TACHI, Toshimasa TAKANISHI, Hatsuko SUZUMURA and Hidemaro TAKEYAMA

Health Sciences of Life, Work and Environment, Department of Environmental Health Science and Health Promotion, Graduate School of Medical Sciences, Nagoya City University, Japan

Abstract: Estimation of Energy Expenditure during Sedentary Work with Upper Limb Movement: Kunio TSURUMI, *et al.* Health Sciences of Life, Work and Environment, Department of Environmental Health Science and Health Promotion, Graduate School of Medical Sciences, Nagoya City University—This study aims to evaluate the availability of surface-electrode electromyogram (EMG) and acceleration to predict energy expenditure during sedentary work with upper limb movement. The following variables were measured in 12 female subjects: oxygen consumption (VO_2), heart rate, EMG from the medial and anterior part of the deltoid muscle, and acceleration of wrist movement. The subjects were requested to perform four different sedentary tasks. In tasks 1, 2 and 3, subjects touched two points on a table (height 70 cm) alternatively. The distance between the two points was 50 cm in tasks 1 and 3, and 100 cm in task 2. The frequency of the movement was 100 touches per minute in tasks 1 and 2, and 152 touches in task 3. In task 4, the points were located vertically on a wall, so they had to move their upper limb vertically in this task. The height of the points was 10 cm below and 40 cm above the acromion height of the subject, and task frequency was 100 touches per minute. The correlation coefficient was 0.285, 0.581 and 0.676, between VO_2 and heart rates, VO_2 and acceleration, and VO_2 and EMG from the deltoid, respectively. The coefficient of determination was 0.648, when employing multiple regression analysis, with acceleration and EMG as independent variables. These results suggest that energy expenditure during sedentary work with upper limb movement can be well estimated by using the data from acceleration of wrist movement and the EMG of

the deltoid.

(J Occup Health 2002; 44: 408–413)

Key words: Energy expenditure, Heart rate, Acceleration, Electromyogram

Estimation of the energy expenditure during work is important for making out a prescription for exercise as well as improving the physical workload. Convenient ways to measure energy expenditure during work include measurement of heart rate, number of steps with pedometer devices, and acceleration at the lower back with an accelerometer etc. But such methods have shortcomings. Food intake, temperature and the psychological states of subjects influence the heart rate, especially in the steady state^{1–3}. Motion sensors also can not be used to determine the static characteristics of physical activity^{2,4}, since such methods can not accurately measure energy expenditure during the steady state, e.g., sedentary work. In this experiment, therefore, we investigated the accuracy of three methods during sedentary work (e.g., assembly work using the upper limbs) in order to compare relatively small amounts of energy expenditure without movements of the trunk: measurement of heart rate, acceleration of the wrist movement and surface-electrode electromyogram (EMG) of the medial and anterior part of the deltoid.

Methods

The subjects were 12 healthy, right-handed female students aged 19–22 (average 19.5, SD 1.0) years old, whose height and weight were 145–163 (average 156.8, SD 4.8) cm and 42–57 (average 49.0, SD 4.8) kg, respectively. Approval was obtained from the Ethics Committee of the Nagoya City University Medical School. Informed, written consent was obtained from each subject.

Oxygen consumption: The concentration of oxygen in

Received Feb 28, 2002; Accepted July 18, 2002

Correspondence to: N. Tachi, Health Sciences of Life, Work and Environment, Department of Environmental Health Science and Health Promotion, Graduate School of Medical Sciences, Nagoya City University, 1 Kawasumi, Mizuho-cho, Mizuho-ku, Nagoya 467-8601, Japan

expired gas and ventilation volume were measured by means of a metabolic analyzer (TEEM100; Aero Sport Inc., USA), and the average oxygen value for 1 to 4 min after starting the task was used for the analysis. The rest value (average 0.16, SD 0.02) ($\text{l}\cdot\text{min}^{-1}$) was measured before the first task. To calculate the increased energy expenditure value (kcal) for the task, the rest value was deducted from oxygen consumption (VO_2) ($\text{l}\cdot\text{min}^{-1}$) during the task, multiplied by 5 and divided by individual weight⁵⁾.

Heart rate: The subjects wore bandage style heart rate monitors (Polar Vantage NV; Polar Electro Oy., Finland) on their chests, and the heart rate was recorded with a TEEM100. The rest value (average 79.6, SD 9.1) ($\text{beats}\cdot\text{min}^{-1}$) was measured before the first task. The heart rate at rest was deducted from the average heart rate between 1 and 4 min after the task started, because the heart rate became constant 1 min after a task began. This value was used as an indicator of the increase in heart rate.

Wrist movement acceleration: The acceleration of the subject's right wrist movement was measured by means of a triaxial accelerometer (TA-513G; Nihon Koden Inc., Tokyo, Japan) and recorded on a data recorder. The absolute values for acceleration magnitude sampled at

50 Hz were used to calculate the average acceleration of each dimension per second (a_x , a_y , a_z). These average accelerations were integrated with the following equation⁶⁾:

$$\text{IAV} = \int_{t=0}^T \sqrt{a_x^2 + a_y^2 + a_z^2} dt$$

Where IAV=integral of magnitude of the total acceleration vector

a_x =average acceleration of x dimension per second

a_y =average acceleration of y dimension per second

a_z =average acceleration of z dimension per second

We used the average value from 1 to 4 min after tasks started. The sensor was applied to the subject's wrist by a watchband with acrylic resin (Pattern Resin; GC Corp., Tokyo, Japan) (Fig. 1).

EMG of the deltoid muscle: the action potential of the anterior and medial parts of the right deltoid was recorded by means of surface electrodes with a muscle tester (ME3000P; Mega Electronics Ltd., Kuopio, Finland) (Fig. 2). There is an exponential relationship between integrated EMG activity and muscle tension⁷⁾. Thus we calculated the logarithm of the ratio between the obtained values and the values at maximal voluntary contraction.

The subjects performed four different tasks in all of

Fig. 1. Triaxial accelerometer fixed by a watchband.

Fig. 3. Subject engaged in task 2.

Fig. 2. Location of EMG electrodes.

Fig. 4. Subject engaged in task 4.

which they were asked to move their upper limbs in a sitting posture. The subjects were to alternately touch two squares with the middle finger of their right hand in all tasks. The distance between the two squares, and the speed (frequency) and direction of the movements varied with the task. In tasks 1–3, the squares were indicated on a horizontal table. The table height was 70 cm, and the subject was asked to perform the tasks sitting on a chair (45 cm off the floor). The chair was placed where the subject's right acromion would be in the center between the 2 marks. In task 4, two squares were indicated on a vertical wall, and the height of the chair was adjusted so that the subject's right acromion was 10 cm below the lower of the two squares. The speed of the hand movement was paced with a metronome. In tasks 1–3, the hand movement was horizontal, but in task 4 it was vertical. In task 2, the distance between the squares was 100 cm, against 50 cm in the other tasks. In task 3, the touching speed was 152 times per minute, and 100 times per minute in the other tasks.

Each task was performed for 4 min. There was a 5-

min rest between tasks. The tasks were done in random sequence. Figs. 3 and 4 show the subjects engaged in tasks 2 and 4, respectively.

The data were statistically analyzed with SPSS 9.0J for Windows.

Results

We could get useful data on 48 sets from 12 subjects. In 29 sets all measurement results were obtained. We used these data for multiple linear regression analysis. The data obtained with each device in the four tasks are shown in Fig. 5. The variance of increase in the heart rate among the subjects was large in task 4. The estimated energy expenditure with acceleration was higher than that estimated by other methods in task 3.

Correlation: Fig. 6 shows the relationship between an increase in energy expenditure calculated from the oxygen consumption and heart rate, acceleration of the right wrist movement, EMG amplitude of the medial part of the right deltoid muscle, and EMG amplitude of the anterior part of the right deltoid muscle, respectively.

Fig. 5. Data obtained by each method in four tasks.

Fig. 6. Relationship between increase in energy expenditure and value obtained by each method.

The correlation between the increase in heart rate and the energy expenditure in task 4 was different from those in tasks 1–3. The correlation coefficient in tasks 1–3 was 0.746 with significance ($p < 0.01$), but the correlation coefficient was lower when the results obtained from task 4 were included. The overall correlation coefficient was 0.285 (not significant).

The correlation coefficient between acceleration and energy expenditure was 0.581 ($p < 0.01$) when the data obtained from tasks 1–4 were used, whereas the correlation coefficient was 0.608 ($p < 0.01$) without task 4 data. Unlike the correlation of heart rate and the energy expenditure, there were no significant differences between the data with and without task 4 data.

Table 1. Results of multiple linear regression analysis

independent variable	partial regression coefficient	standard mean error	standardized coefficient	significance level
(constant)	1.095×10^{-02}	.004		.009
EMG (med. deltoid)	8.794×10^{-03}	.002	.564	.000
IAV	4.082×10^{-05}	.000	.400	.003
n=29	$R^2=0.648$			$p < .001$

independent variable: stature, heart rate increase, acceleration of wrist (integral of magnitude of total acceleration), EMG from medical part of deltoid (logarithm of ratio of obtained values to values at maximal voluntary contraction)

dependent variable: increase in energy expenditure per weight

The coefficients of correlation between the increase in energy expenditure and the EMG of the medial and anterior parts of the deltoid were 0.676 ($p < 0.01$) and 0.559 ($p < 0.01$), respectively. Without the data from task 4, the correlation coefficients were 0.710 and 0.559, respectively.

Multiple linear regression analysis: When the increased amount of energy expenditure per weight was the dependent variable, and stature, values from heart rate, acceleration and EMG (the medial part of the deltoid) were the independent variables, R^2 of the multiple linear regression analysis was 0.674. If EMG data were not used as independent variables, R^2 was 0.406. Variables of acceleration and EMG (the medial part of the deltoid) were selected by stepwise selection. The calculated value for R^2 in the multiple linear regression analysis with variables selected by stepwise selection was 0.648 (Table 1).

Discussion

The heart rate is widely used to assess physical activity because it is easy, measurable for a long period, and has a linear relationship with the level of oxygen consumption. The heart rate also reflects relative stress placed on the cardiopulmonary system as a result of physical activities^{8,9}. But Blackburn and Calloway¹⁰ commented that prediction of the energy expenditure from the heart rate is unreliable in the range 80–120 beats/min. Slopes of regression have different coefficients in the steady state and in the walking state, and these two slopes match at 80–120 beats/min. In other words, one must use two different equations depending on the heart rate, yet there is no clear-cut line between the two states⁸. Emotional stress can increase the heart rate without physical activity^{2,3}, and the heart rate-oxygen consumption relationship is moderated by the proportion of active muscle mass and whether the activities are continuous or not¹¹. Furthermore, the normalization of heart beats to the baseline after physical activities takes more time than the recovery of the amount of oxygen consumption¹¹. Especially at the low activity level, heart rates are influenced by emotions, food, temperature and activity just before the measurement¹¹.

In this experiment, we found a statistically significant correlation of 0.746 ($p < 0.01$) between the increase in heart rate and the increase in energy expenditure during tasks 1–3. Throughout the experiment, in all tasks the correlation coefficient was 0.285 (not significant). Because the subjects were in an unusual situation, facing walls during the experiment in task 4, the subjects' heart rates seemed to have increased excessively. Since the level of activity was relatively low in this experiment, the mental stress on the subjects may influence the results of the experiment.

Wong *et al.*¹² were the first to use a portable accelerometer to measure energy expenditure. Because

activities of human beings are complex and multidirectional, it is suggested that a triaxial accelerometer is superior to a uni-axial accelerometer^{13–16}. For example, Eston *et al.*² compared the accuracy of heart-rate monitoring, pedometry, triaxial accelerometry and a uniaxial accelerometer for estimating oxygen consumption during typical children's activities. As a result, a multiple-regression equation, that included triaxial accelerometry counts and heart rate, predicted oxygen consumption better than any measure alone ($R^2 = 0.85$), and the best single measure to predict oxygen consumption was triaxial accelerometry ($R^2 = 0.83$). The authors concluded that a triaxial accelerometer provides the best assessment of activity.

On the other hand, motion sensors such as a pedometer are considered not to be able to measure the energy expenditure in static work such as lifting heavy objects². The same thing can be said for an accelerometer attached to the lower back. Under daily living conditions, static activity might be only a negligible part of total activity. But those engaged in sedentary occupations are exceptions. The disadvantage of the accelerometer is its low sensitivity to sedentary activities and the inability to register static exercises⁴. Nishihara and Sakamoto¹⁷ compared the acceleration method with the time and motion study method. In their study, the largest difference between predicted energy expenditure estimated by two methods was carpenter's work such as hammering and planing. An acceleration sensor at the waist could not recognize these activities.

We therefore attempted to estimate the increase in energy expenditure due to movements of the upper limbs when the subject was seated. We attached a triaxial accelerometer with a watch belt to measure the acceleration of the wrist movements. The watchband was easily worn and the accelerometer was securely attached to it to prevent it from moving during task performance. Unlike the estimation by means of heart rate, the coefficient of correlation between energy expenditure and acceleration of wrist movement during task 4 was not different from that during tasks 1–3. Overall, the coefficient of correlation between the increase in energy expenditure and the method of measuring acceleration was 0.581, reflecting a better result than by measuring the heart rate.

Servais *et al.*¹⁸ concluded that an accelerometer on the waist overestimated the energy expenditure when a subject performed an activity which tended to create great acceleration such as jumping rope. On the other hand, when a subject engages in an activity with less acceleration, such as climbing stairs at the same speed, an accelerometer underestimates the energy expenditure. In task 3, the movements of the arms were frequent and quick, so the acceleration was large and the energy expenditure was overestimated.

To the best of our knowledge, no study to date has estimated energy expenditure from the EMG, but in the present experiment there was a close correlation between the increase in energy expenditure and the EMG predicted value for the medial part of the deltoid ($r=0.676$, $p<0.01$). A correlation was also observed in the predicted value from the EMG of the anterior part of the deltoid ($r=0.559$, $p<0.01$). According to the results of multiple linear regression analysis, R^2 was 0.406 when the increased amount of energy expenditure per weight was the dependent variable and stature, heart rate and acceleration were the independent variables. By adding EMG data to the independent variables, R^2 was increased to 0.674. Moreover, when we used a step-wise selection method, EMG (the medial part of the deltoid) and acceleration values were selected ($R^2=0.648$).

As mentioned above, an accelerometer can not measure static movements, as when lifting heavy objects. It is suggested that EMG measurement can reduce the inaccuracy and underestimation of the predicted value by an accelerometer during static activity.

The EMG device used in this study was somewhat sophisticated. A simpler version can be used to measure only amplitude of the EMG.

We studied the effectiveness of using the EMG of the medial part of the deltoid, in conjunction with measuring the acceleration of wrist movement, to estimate the increase in energy expenditure during static work with upper limb movements, e.g., lifting small objects in a sitting or standing state, grinding with a coffee mill or assembly work in a sitting position. The use of the EMG of the medial part of the deltoid provides greater accuracy in predicting energy expenditure during static work.

The deltoid muscle activity is observed during upper limb movement generally, but in special cases such as when the elbow joint is supported with an armrest or a table board, the EMG of the deltoid may not be useful for predicting energy expenditure. Further research is necessary to examine the accuracy of this method for predicting energy expenditure in actual working conditions.

Acknowledgments: This study was supported in part by Grants-in-Aid from the Ministry of Education, Science, Sports and Culture of Japan (07557038).

References

- 1) KJ Acheson, IT Campbell, OG Edholm, DS Miller and MJ Stock: The measurement of daily energy expenditure: an evaluation of some techniques. *Am J Clin Nutr* 33, 1155–1164 (1980)
- 2) RG Eston, AV Rowlands and DK Ingledew: Validity of heart rate, pedometry, and accelerometry for predicting the energy cost of children's activities. *J Appl Physiol* 84, 362–371 (1998)
- 3) WHM Saris: Habitual physical activity in children: methodology and findings in health and disease. *Med Sci Sports Exerc* 18, 253–263 (1986)
- 4) CV Bouten, KT Koekkoek, M Verduin, R Kodde and JD Janssen: A triaxial accelerometer and portable data processing unit for the assessment of daily physical activity. *IEEE Trans Biomed Eng* 44, 136–147 (1997)
- 5) William DM, Frank IK and Victor LK: Human energy expenditure during rest and physical activity. In: *Exercise Physiology*. Baltimore: Williams & Wilkins, 1996: 151–164.
- 6) CV Bouten, KR Westerterp, M Verduin and JD Janssen: Assessment of energy expenditure for physical activity using a triaxial accelerometer. *Med Sci Sports Exerc* 26, 1516–1523 (1994)
- 7) PV Komi and JH Vitasalo: Signal characteristics of EMG at different levels of muscle tension. *Acta Physiol Scand* 96, 267–276 (1976)
- 8) GB Spurr, AM Prentice, PR Murgatroyd, JC Goldberg, JC Reina and NT Cristman: Energy expenditure from minute-by-minute heart rate recording: comparison with indirect calorimetry. *Am J Clin Nutr* 48, 552–559 (1988)
- 9) JR Welsman and N Armstrong: Daily physical activity and blood lactate indices of aerobic fitness in children. *Br J Sports Med* 26, 228–232 (1992)
- 10) MW Blackburn and DH Calloway: Heart rate and energy expenditure of pregnant and lactating women. *Am J Clin Nutr* 42, 1161–1169 (1985)
- 11) Klausen K, Rasmussen B, Glensgard LK, Jensen OV. In: *Children and Exercise XI*, edited by Binkhorst RA, Kemper HCG, and Saris WHM. (Eds.) Work efficiency during submaximal bicycle exercise. Champaign IL: Human Kinetics, 1985: 210–217.
- 12) TC Wong, JG Webster, HJ Montoye and R Washburn: Portable accelerometer device for measuring human energy expenditure. *IEEE Trans Biomed Eng* 28, 467–471 (1981)
- 13) TG Ayen and HJ Montoye: Estimation of energy expenditure with a simulated three-dimensional accelerometer. *Journal of Ambulatory Monitoring* 1, 293–301 (1988)
- 14) CE Matthews and PS Freedson: Field trial of a three-dimensional activity monitor: comparison with self report. *Med Sci Sports Exerc* 27, 1071–1078 (1995)
- 15) JF Nichols, P Patterson and T Early: A validation of a physical activity monitor for young and older adults. *Canadian Journal of Sport Science* 17, 299–303 (1992).
- 16) PD Swan, WC Byrnes and EM Haymes: Energy expenditure estimates of the Caltrac accelerometer for running, race walking, and stepping. *Br J Sports Med* 31, 235–239 (1997)
- 17) T Nishihara and M Sakamoto: Estimation of daily energy expenditure by a new calorie meter which distinguishes between sitting and standing activities. *J. Science of Labour* 72, 49–60 (1996) (in Japanese)
- 18) SB Servais, JG Webster and HJ Montoye. Estimating human energy expenditure using an accelerometer device. *Journal of Clinical Engineering* 9, 159–170 (1984)