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A Preliminary Study on Estimation of Energy Expenditure at Different Locations of Acceleration Sensor during Submaximal Exercise

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Abstract—**The purpose of this study is, for estimating energy expenditure with triaxial accelerometers during exercise, to compare determination coefficients of equations of the estimated regression according to several locations of the accelerometers on the body and then to present an estimation model on the location where there is the least restriction on physical activities.**

A small portable device that is able to obtain acceleration data during exercise was developed. It was attached on the back, wrist, knee and ankle of the body and then submaximal exercise was conducted on treadmills with the Bruce protocol. For the experimentation, seventeen males of twenties and thirties in good health (27.23±2.18) participated and wore the equipment to analyze respiratory gas, so that the values of acceleration and energy expenditure from the respiratory gas analyzer could be obtained at the same time. The energy expenditure values from the outputs of the respiratory gas equipment were set as a base value, and the accelerations and the physical features of the participants (age, weight, height and BMI) as variables, to check each correlation, and for each of the four locations of the accelerometers on the body, regression analysis was carried out. The results of the experiment are as follows: the correlation between the acceleration and the energy expenditure was the highest on the knee and the lowest on the wrist; but, the determination coefficients (R^2) of the regression equations using the continued hours of exercise, weight and acceleration values did not show significant difference among the locations on the body, as the highest R^2=0.873 on the back and the lowest R^2=0.852 on the wrist. This study has shown two possibilities. First, it is possible to predict energy expenditure using accelerometer sensor without respiration gas analyzer in laboratory situation. Second, these findings can be applied to application about predicting conveniently energy expenditure during outdoor activities using accelerometer on watch or shoes.

I. Introduction

When measuring the quantity of motion in everyday living, it is needed to use objective and reliable technology. The quantity of motion, from a physiological viewpoint, can be regarded as the result of movement of muscles or expenditure of energy [1]. To calculate the quantity of motion of humans, we can use calorimeters that analyze concentrations of carbon dioxide or heat loss in a closed system, but the system of calorimeters have several shortcomings of expensiveness, large size and being difficult to carry. The heart rate is used to estimate energy expenditure [2][3][4][5][6]. Heart rate meters are relatively low-priced and are able to store data of several days or weeks, thereby presenting the data of exercise patterns such as frequency, intensity and continuation [7]. Heart rates, however, show some limitations as they are easily affected by emotional or environmental conditions, training state and so on [8]. There have been demands for simple and inexpensive devices allowing test subjects to carry that are capable of measuring physical activities or energy expenditure for a considerable period. Meanwhile, it was found out that body mass and accelerations of arms and legs have something to do with energy expenditure [10], which is consequently leading to new technologies to measure energy expenditure by attaching motion sensors to the human body and detecting motions, for the purpose of developing much smaller and portable systems of the quantity of motion [11]. Acceleration sensors have been considered to be a most suitable motion sensor for calculating the quantity of motion, and used for decades in research in to motions like walking [12]. Such acceleration sensors were used based on the evidence proving close relations between outputs of the sensors and energy expenditure [13][14][15][16]. The accuracy of accelerators, which are frequently used both in laboratory and field tests to find out energy expenditure of motions, is a critical factor that should be considered to measure an optimum energy expenditure in everyday living [17]. This study was to develop a small device with a built-in triaxial accelerometer for measuring energy expenditure of people during exercise and then was to do an experiment to examine relations between energy expenditure and equations of the quantity of motion using acceleration signals at each of body parts.

II. Method

A. Subjects

This study, by measuring energy expenditure of males of twenties and thirties in good health during walking or running exercise on treadmills, is to present the method to improve validity of estimates of energy expenditure, measured with triaxial accelerometers. For the purpose above, the experiment was carried out, aiming at the seventeen

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subjects who do not show any non-selection reasons from the viewpoint of genetics and physique and who have no history of disease cases restricting the exercise experiment.

TABLE I
PHYSICAL CHARACTERISTICS OF SUBJECTS

Sex(N)		Age(years)	Height(*cm*)	Weight(*kg*)	BMI
Male (N = 17)	Mean	27.23	174.28	69.03	22.75
	SD	±2.18	±4.33	±6.49	±2.26

B. Measuring Instruments

The measuring instruments used to estimate energy expenditure during treadmill exercise and their purposes are shown in Table 2.

TABLE II
MEASURING INSTRUMENTS AND THEIR PURPOSES

Instrument	Model Name	Purpose
Gas Analyzer	TrueOne 2400, PARVO MEDICS	To measure energy expenditure by analyzing respiratory gas during exercise
Treadmill	TM55, QUINTON	To control exercise load
Automatic Measurer of Height and Weight	DS-102, D.S. JENIX	To measure heights and weights
Measurer of Body Fat	BoCA X2, MEDIGATE	To measure BMI
Collector of Triaxial Acceleration Data	In-house product	To measure and store variations from triaxial accelerators, which are output by body movement during exercise

1) Fabrication of a Collector of Acceleration Data

A device that is able to measure the variation in values from the triaxial acceleration sensors during exercise and to save those values was designed and fabricated in this study. The device was composed of a signal collector, controller, saving unit and power unit.

MMA7260Q, Freescale Semiconductor was used as the triaxial acceleration sensor to get signals during exercise, MSP430f2418 as the low-power controller to process data and micro SD memory as a saving unit to store data during exercise, and portable lithium polymer rechargeable batteries were used for participants not to have restrictions on their motion during exercise.

Figure 1 shows the fabricated collector of triaxial acceleration data. A Weight of the fabricated collector is 20.7g. The data fluctuation on the three axes during exercise was obtained by setting the sampling frequency to 100Hz and the fluctuation on each axis, that is, x, y, z, was saved separately in files in the micro SD memory. All accelerometer signals were digitally processed by controller. The x-axis is back-and-forth movement, the y-axis up-and-down and the z-axis right-and-left.

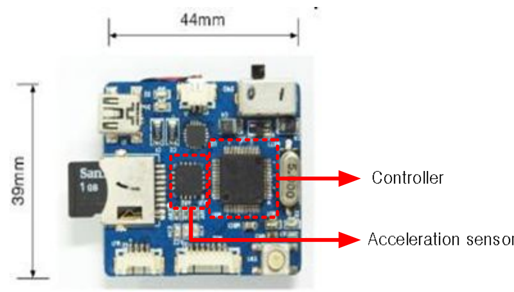

Fig. 1. Fabricated Collector of Triaxial Acceleration Data

C. Experiment Methods and Procedure

To estimate the intensity of treadmill exercise and energy expenditure according to exercise hours, an automatic gas analyzer was used to analyze respiratory gas and measure energy expenditure during exercise.

Excessive exercise, which can affect subjects' exercise ability, was not allowed for two days before the experiment so that they could be in good physical condition during the experiment.

As shown in Figure 2, the triaxial accelerometers were attached on the back, wrist, knee and ankle to estimate energy expenditure according to the locations on the body.

Fig. 2. Locations and Directions of Triaxial Accelerometer Attachment

For the exercise load test, treadmills of which speed and incline can be controlled were used and the Bruce protocol that increases the speed and incline at the same time was used to change the strength of exercise load. For the subjects' safety, the exercise load was reduced to the least level and after six minutes of recovery, the experiment was closed in case during the load test, the specialist judged the subjects to reach their maximum ability of exercise or the subjects themselves expressed the limitation of their exercise power.

D. Integral Transform of Acceleration Data

When using the accelerometer signals to estimate energy expenditure, integrals of the signals were set as a variable. As a prior process of the integration of signal intensities, the high pass filter of 0.5Hz was applied to obtained signals to remove the baseline and signal offset, as shown in Figure 3(b). The signals on the negative area shown in Figure 3(b) are the ones showing the accelerator location doing backward motion in reaction to its opposite location on the body doing forward movement during the treadmill exercise. Since the signals of this area can be regarded as exercise intensities, the absolute values of the signals were used as shown in Figure 3(c), and then all the signal intensities at each sampling distance were added to use them as acceleration values in statistical processing.

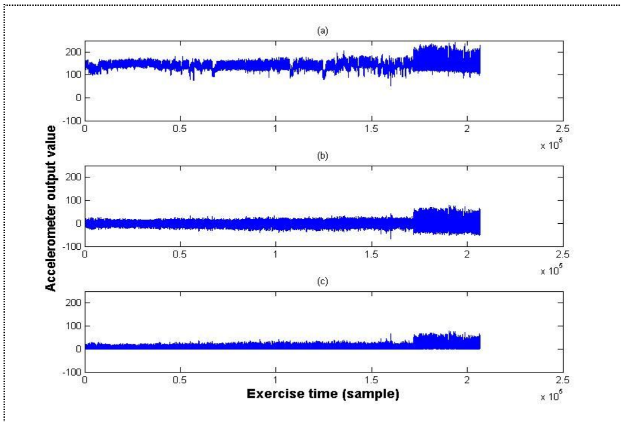

Fig. 3. Signal Processing of accelerometer signal.

(a) Original Signals of Accelerometer. (b) Original Signals less Offset. (c) Absolute Values of (b) Signals.

E. Statistical Analysis

The output data were analyzed with SPSS 15.0, Windows program. To examine the relationship between independent and dependent variables, Pearson's r was calculated, and multiple regression was done to get the coefficients of determination (R^2) for each model having multi-variables according to the accelerator locations. The significance level was $p<.05$.

III. RESULT

A. Examination of Variables' Significance for Regression Analysis

Pearson's correlation analysis was done to check the significance of the variables for regression analysis.

As shown in Table 3, the variations of the accelerators attached on the body and the continued hours of exercise were found to have significant correlation with the change in energy expenditure during exercise, and among the acceleration data of the several locations, those of the knee and the ankle showed the highest correlation; but age(r=-0.088), height(r=0.229), weight(r=0.403) and BMI(r=0.348), which are the physical features of the subjects, were observed to have a relatively little correlation with energy expenditure compared with the acceleration signals (max : r=0.830, min : r=0.582) and the continued hours of exercise (r=0.829).

B. Regression Analysis of Multi-Variables Models with Triaxial Accelerometers

Table 4 shows the coefficients of determination (R^2) of the multiple regression analysis to estimate energy expenditure according to the triaxial accelerometer locations.

TABLE III
The correlation between energy expenditure and each variable

x_back	Pearson Correlation	.717	*
	Sig. (2-tailed)	.000	
y_back	Pearson Correlation	.701	*
	Sig. (2-tailed)	.000	
z_back	Pearson Correlation	.771	*
	Sig. (2-tailed)	.000	
x_wrist	Pearson Correlation	.645	*
	Sig. (2-tailed)	.000	
y_wrist	Pearson Correlation	.582	*
	Sig. (2-tailed)	.000	
z_wrist	Pearson Correlation	.600	*
	Sig. (2-tailed)	.000	
x_knee	Pearson Correlation	.830	*
	Sig. (2-tailed)	.000	
y_knee	Pearson Correlation	.822	*
	Sig. (2-tailed)	.000	
z_knee	Pearson Correlation	.790	*
	Sig. (2-tailed)	.000	
x_ankle	Pearson Correlation	.808	*
	Sig. (2-tailed)	.000	
y_ankle	Pearson Correlation	.807	*
	Sig. (2-tailed)	.000	
z_ankle	Pearson Correlation	.764	*
	Sig. (2-tailed)	.000	
Age	Pearson Correlation	-.088	*
	Sig. (2-tailed)	.000	
Height	Pearson Correlation	.229	*
	Sig. (2-tailed)	.000	
Weight	Pearson Correlation	.403	*
	Sig. (2-tailed)	.000	
BMI	Pearson Correlation	.348	*
	Sig. (2-tailed)	.000	
Exercise Time	Pearson Correlation	.826	*
	Sig. (2-tailed)	.000	

*p < .05

Sig. = significant probability

TABLE IV
Result of the multiple regression analysis by the change in the locations of triaxial Accelerometer

Model	R	R^2	Adjusted R^2	SEE
1 ACC at back +Exercise Time+Weight	.934	.873	.872	.37022
2 ACC at wrist +Exercise Time+Weight	.923	.852	.851	.39921
3 ACC at knee +Exercise Time+Weight	.925	.856	.855	.39379
4 ACC at ankle +Exercise Time+Weight	.930	.864	.863	.38302

Dependent Variable: Energy Expenditure

The independent variables of the regression equation are the acceleration signals at each location, continued hours of exercise, and weight (r=0.403) which shows the greatest correlation with energy expenditure among the physical feature variables. The determination coefficient of the regression equation with the acceleration signals was the highest on the back (R^2=0.873) and the lowest on the wrist (R^2=0.852), accordingly showing that there are few changes in the determination coefficients of the regression equations according to the locations.

Figure 4 shows the relationship between the energy expenditure measured through the respiratory gas analysis and the estimated energy expenditure drawn from the regression analysis for Model 1 in Table 4.

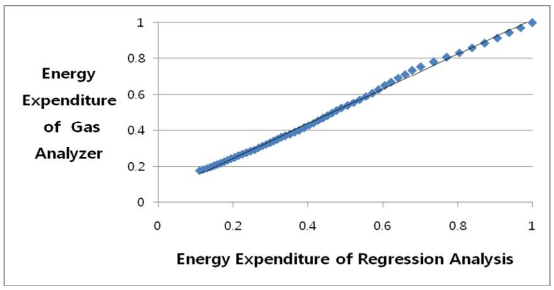

Fig. 4. The Diagram of Scatter between the Reference Energy Expenditure during Exercise and the Estimated Ones

IV. Discussion & Conclusion

This study, as preliminary research to estimate energy expenditure during exercise, was conducted to develop the small devices with built-in triaxial acceleration sensors for comparing energy expenditures according to accelerator locations; to find out the correlation between subjects' physical features and energy expenditure; and to examine relations between energy expenditure and equations of the quantity of motion using acceleration signals at each of body parts.

The correlation between the subjects' physical feature variables and energy expenditure was found out to be relatively little, as r=-0.088 (age), r=0.229 (height), r=0.403 (weight) and r=0.348 (BMI), compared with the correlation between energy expenditure and the acceleration signals (max : r=0.830, min : r=0.582) and the continued hours of exercise (r=0.829). The correlation between energy expenditure and the acceleration signals at the locations was the highest at the knee, followed by the ankle, back and wrist.

Based on the correlation between energy expenditure and each variable, the multiple regression analysis with the variables of weight, continued hours of exercise and acceleration signals was carried out, and as a result, the determination coefficients of the regression equations at the back, wrist, knee and ankle were 0.873, 0.852, 0.856 and 0.864, respectively.

This result is the same as that of the research by Leeders, et al. (2000) showing that in case basic data of Yamax Digiwalker step-count (Digi walker) and Tritrac, CSA accelerators come to be related with the average energy expenditure of physical activities, there is similar correlation [18]. The coefficients of determination of the multiple regression analysis did not show significant difference by the change of accelerometer sensor in the body locations.

This study has shown two possibilities. First, it is possible to predict energy expenditure using accelerometer sensor without respiration gas analyzer in laboratory situation. Second, these findings can be applied to application about predicting conveniently energy expenditure during outdoor activities using accelerometer on watch or shoes.

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