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Original Article

Evaluation of walking time according to walking speed using a triaxial accelerometer system

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ABSTRACT
Miura S, Satake M, Tamura Y, Ikeda M, Kawagoshi A, Sugawara K, Takahashi H, Homma M, Sakata S, Shioya T. Evaluation of walking time according to walking speed using a triaxial accelerometer system. Jpn J Compr Rehabil Sci 2013; 4: 73−79.
Purpose: The primary purpose of this study was to quantify the walking time in daily life as slow and fast walking times using a newly improved triaxial accelerometer system. The secondary purpose was to study the slow and fast walking times of healthy young and elderly adults and stable patients with chronic obstructive pulmonary disease (COPD) using this system.
Methods: Twenty-six healthy young subjects, 15 healthy elderly adults, and 11 stable COPD patients participated in this study. The subjects' time spent walking, standing, sitting, and lying down were assessed using an activity monitoring and evaluation system (A-MES™). We evaluated the slow and fast walking times according to changes in the detection threshold in the system's software.
Results: The distinguishing speed was found to be 2 km/h, and thus we divided the subjects' walking time into slow (<2 km/h) and fast (≥2 km/h) walking using 2 km/h to distinguish the speed. Ninety-five percent of the walking measured by the A-MES™ was slow walking. The fast walking time of the stable COPD patients was significantly shorter than that of the healthy young and elderly adults ($p<0.01$).
Conclusion: These results suggest that walking time in daily life can be differentiated as slow (<2 km/h) and fast (≥2 km/h) walking using a new triaxial accelerometer system.
Key words: physical activity, triaxial accelerometer, slow walking (<2 km/h), fast walking (≥2 km/h), walking time

Introduction

Low levels of physical activity continue to be a focus of attention as a risk factor for lifestyle-related diseases [1−4]. Accurate measurement of a patient's physical activity is important for the selection of therapeutic approaches and the development of rehabilitation programs in practice [1, 2]. It is difficult, however, to accurately and easily assess physical activity, and there is no international standardized assessment for physical activity at present [3, 4].

Although questionnaire-based measures are often used to assess physical activity in clinical practice, memory recall problems, misinterpretation, and incomplete forms affect the results, and thus questionnaire-based measures are not suitable, particularly for elderly adults and children [5−8]. Monitoring instruments such as pedometers and accelerometers provide objective and relatively easy measures of physical activity compared with other

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methods, and consequently, many instruments have been developed based on these advantages [4, 8]. The use of an accelerometer is currently the most common method of assessing physical activity, but the variety of available accelerometers provide different measures, including step counts, exercise intensity and energy expenditure, which are not standardized [4, 7, 8]. In addition, it is critical to discriminate between slow and fast walking speeds since walking is the most basic form of physical activity, and the level of physical activity differs according to walking speed.

We recently reported our development of a new triaxial accelerometer system for the assessment of daily physical activity, which measures daily walking, standing, sitting and lying times [9−11]. Walking speed is a more objective measure for the assessment of physical activity, and dividing the calculated walking time by walking speed could enable more precise assessments of physical activity. The primary objective of the present study was to assess walking speed by grouping “slow walking” and “fast walking” through modifications of the analytical program in the triaxial accelerometer system. The secondary objective was to assess daily “slow walking” and “fast walking” in healthy young adults, healthy elderly adults, and patients with chronic obstructive pulmonary disease (COPD) using this new assessment system. We included COPD patients for the analyses because they may walk slower than healthy adults due to decreased respiratory function.

Subjects and Methods

1. Subjects

Twenty-six healthy young adults (13 males, 13 females, age 22.3±3.7 years (mean±SD); young adults), 15 healthy elderly adults (6 males, 9 females, age 73.1±3.3 years; elderly adults) who attend group activities at a local community center, and 11 stable COPD patients (10 males, 1 female, age 78.8±6.4 years; COPD) who go to Hospital A participated in this study. Individuals who reported engaging in heavy exercise or in sports club activities were excluded. Six of the COPD patients were under home oxygen treatment. Characteristics of the subjects are given in Table 1. This study was reviewed and approved by the Ethics Committees (2011) of University Graduate School of Medicine A and Hospital A, and was carried out in conformity with the Declaration of Helsinki [12]. Written consent was obtained from all the subjects.

2. Instrumentation and Measurement

The assessment of physical activity in daily life was done using a new triaxial accelerometer system (Activity Monitoring and Evaluation System [A-MES™], Solid Brains, Kumamoto). The A-MES™ consists of two sensors (69 H×44 W×11.5 D mm each, weight: 28 g each), a station, and analytical software used with a personal computer. These sensors are so small and light that they can be attached on the thigh and the chest of the subject wearing clothing with two pockets (Fig. 1).

The A-MES™ system measures posture and movement (lying down, sitting, standing, and walking) by using a three-dimensional analysis of acceleration

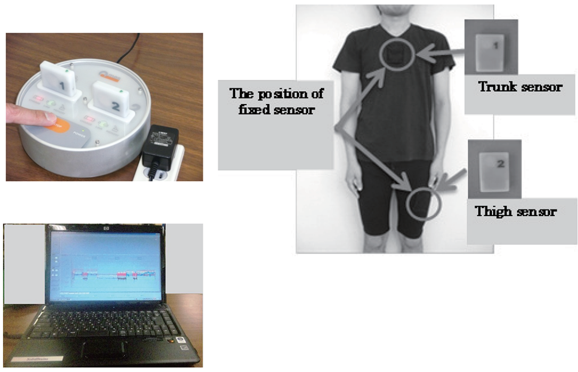

Figure 1. Composition of A-MES™ (upper left: station, lower left: analysis software, right: position of each sensor: quoted from reference 11).

Table 1. Characteristics of the subjects.

	Young adults (n=26)	Elderly adults (n=15)	COPD (n=11)
Age (years)	22.3±3.7**[2],**[3]	73.1±3.3**[1]	78.8±6.4**[1]
Height (cm)	166.9±9.2	156.9±6.8	160.0±5.9
Weight (kg)	58.2±9.7	59.7±5.7	55.1±11.7
BMI	20.8±2.1**[2]	24.4±2.8**[1],**[2]	21.4±3.4**[1]
FVC (L)	4.3±1.1**[2],**[3]	2.9±0.5**[1]	2.4±0.6**[1]
FEV_1 (L)	3.8±0.9*[2], *[3]	2.3±0.5*[1]	1.0±0.5*[1]
FEV_1/FVC (%)	88.1±4.9**[3]	76.7±9.4**[3]	42.3±15.8**[1],**[2]
PI_{max} (cmH_2O)	89.1±34.6*[3]	79.8±26.1*[3]	59.9±24.9*[1],*[2]
PE_{max} (cmH_2O)	112.2±48.1*[2],*[3]	91.6±24.0*[1]	90.2±30.3*[1]

*, p<0.05; **, p<0.01; [1], vs young subjects; [2], vs elderly subjects; [3], vs COPD.
BMI (body mass index), FVC (forced vital capacity), FEV_1 (forced effort volume in one second), PI_{max} (maximum inspiratory pressure), PE_{max} (maximum inspiratory pressure).

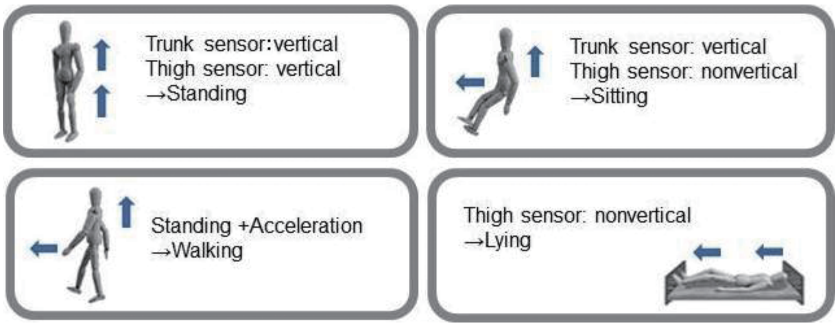

Figure 2. Measurement of position, movement, and postural changes by the A-MES™ sensors (quoted from reference 11).

Figure 3. Actual output waveform in A-MES™.

signals (Fig. 2) [9−11]. Acceleration signals from each sensor attached on the thigh and the chest of the subject and judgment of posture and movement are shown in Figure 3.

The detection threshold of acceleration signals from a three-dimensional acceleration sensor was originally set to detect very slow walking. The detection threshold of acceleration signals is designed to be capable of "xx times" in this acceleration system. Acceleration signals obtained from the sensors were reanalyzed by altering the electrical resistance externally, thus changing the detection threshold in this study.

Pulmonary function was assessed as forced vital capacity (FVC), forced expiratory volume in one second (FEV_1), FEV_1/FVC, and %FEV_1 measured by a spirometer (Chestgraph HI-701™, Chest M.I., Tokyo). Mouth pressure was measured as respiratory muscle strength (PImax, PEmax) using a respiratory dynamometer (Vitalopower KH-101™, Chest M.I., Tokyo) [13, 14].

3. Methods

3.1. Experiment 1: Determination of speed for distinguishing slow and fast walking

The purpose of Experiment 1 was to determine the appropriate walking speed for distinguishing slow and fast walking. Seventeen of the 26 healthy young adults (7 males, 10 females, age 23.1±4.4 years) participated in the experiment. Two sensors (attached to the subject's chest and thigh) collected data as the subjects walked on a treadmill (MAT2600, Fukuda Denshi, Tokyo) at speeds of 2, 3, 4, and 6 km/h, for 5 min each.

After the data was transferred to a personal computer, the walking time at each walking speed was analyzed using the standard threshold; this data is expressed as 100% for the standard value. The walking times were then reanalyzed by changing the threshold of the sensors from "10 times" to "1,000 times", and the reduction rate for distinguishing the walking times was also reanalyzed at each speed. Based on the reduction rates at each speed, we chose the speed that could distinguish the slow and fast speeds as the distinguishing speed.

3.2. Experiment 2: Determination of threshold for distinguishing slow and fast walking

The purpose of Experiment 2 was to determine the threshold that could most efficiently distinguish slow and fast walking. Seven of the 26 healthy young adults (3 males, 4 females, age 21.7±0.5 years) participated in this experiment. Two sensors (attached to the subject's chest and thigh) collected data as the subjects walked on the floor at the slow and fast speeds for 10 min each. Each subject was instructed to walk at a slower speed than the speed that was set after Experiment 1 as slow walking, and then was instructed to walk at a faster speed than the speed that was set after Experiment 1 as fast walking. The subjects were well trained at each walking speed before measurement so that they could maintain constant walking speeds.

After the data was transferred to a personal computer, we analyzed the subjects' walking times at each walking speed using the standard threshold. This data is expressed as percentages of the standard value (100%). The walking times were then reanalyzed by changing the threshold of the sensors from "5 times" to "60 times", and we also reanalyzed the reduction rate of the distinguishing walking time at each speed. The threshold that could distinguish the fast speed with >95% accuracy and that could not distinguish the slow speed with <5% accuracy was identified as the threshold that could distinguish the slow and fast walking.

3.3. Experiment 3: Measurement of daily fast and slow walking times

The purpose of Experiment 3 was to evaluate the daily fast and slow walking times using the distinguishing threshold obtained in Experiment 2. Twenty-two young adults (12 males, 10 females, age 22.3±4.0 years), 15 elderly adults (6 males, 9 females, age 73.1±3.3 years), and 11 stable COPD patients (10 males, 1 female, age 78.8±6.4 years) participated in this experiment.

Two A-MES™ sensors were attached to the subject's chest and thigh to measure the walking times for 12 h over three consecutive days [15]. Only two measurement days instead of three consecutive days were used for one COPD patient due to his worsening symptoms.

Data obtained in this experiment was transferred to a personal computer, and we analyzed the total walking times using the standard threshold. The total walking times were then divided into the fast and slow walking times using the distinguishing threshold obtained in Experiment 2, and the percentages of the fast and slow walking times to the total walking times were calculated.

The experiment was fully explained to each subject with regard to the use of the A-MES™. The subjects were also instructed to wear the A-MES™ from the time they arose from bed in the morning until the time they went to bed at night, except for the time spent bathing. The basic measurement time in this experiment was 12 h, but if a subject's measurement time differed from 12 h, the actual measurement time was converted to 12 h by a conversion calculation.

The number of subjects was fewer in both Experiments 1 and 2 compared to Experiment 3 because of the treadmill requirement in Experiment 1 and the necessity of training for constant walking before Experiment 2.

4. Statistical analyses

The statistical analyses were performed using SPSS software version 11.5J for Windows. The level of significance was set at $p<0.05$. In Experiment 1, we used a one-way analysis of variance (ANOVA) with replications and Bonferroni's multiple comparison for the differences in walking times at each speed. In Experiment 2, we used the non-paired t-test for the comparison of differences in the slow and fast walking times (percentage). In Experiment 3, we used one-way ANOVA with replications and Bonferroni's multiple comparison for the differences in the total walking time, walking times at the slow and fast speeds, and the percentages of walking at each speed among the

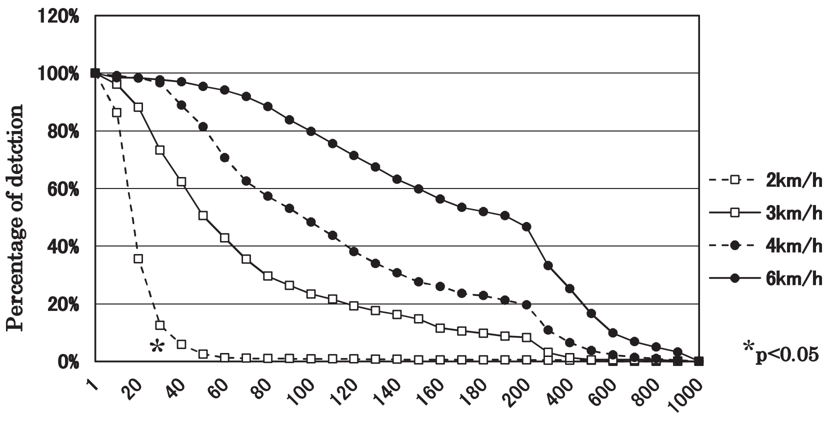

Figure 4. Percentage of each walking speed by each detection threshold.

three groups.

Results

1. Experiment 1: Determination of speed for distinguishing slow and fast walking

The walking times expressed as a percentage of those analyzed using the standard threshold are shown in Figure 4. The walking times are expressed as 100% by the standard threshold, and as the detection threshold was increased, the walking time distinguished at each speed decreased.

When the threshold was set to be 30 times magnification, the percentage of walking distinguished was 72% at 3 km/h and >80% at both 4 km/h and 6 km/h. The percentage of walking distinguished at 2 km/h, 11%, was significantly less compared to the percentages at the other speeds ($p<0.05$). Thus, we selected 2 km/h as the speed that distinguished the slow and fast walking speeds based on these reduction rates at each speed.

2. Experiment 2: Determination of threshold to distinguish slow and fast walking

In Experiment 1, we found that the speed that could distinguish the slow and fast walking from the reduction rates at each speed was 2 km/h. In Experiment 2, the subjects were instructed to walk at the slow speed (<2 km/h) or the fast speed (≥2 km/h), and we then determined the distinguishing threshold.

The results are shown in Figure 5. The subjects' average walking speed at the fast speed (≥2 km/h) was 5.1±0.7 km/h. As the distinguishing threshold increased, the percentage of walking decreased gradually at fast walking (≥2 km/h) from the threshold of "25 times". The percentage of walking decreased quickly at slow walking (<2 km/h) from the threshold of 5 times magnification. The percentage of fast walking (≥2 km/h) was 95% and that of slow walking (<2 km/h) was 5% when the distinguishing threshold of "30 times" was used ($p<0.05$). Based on these results, we chose the threshold that could distinguish the slow (<2 km/h) and fast walking (≥2 km/h) as "30 times".

3. Experiment 3: Measurement of daily fast and slow walking times

The times spent in each posture and the movements of each subject are summarized in Table 2, and the walking times at each speed are given in Table 3. There were significant differences in the total walking times by the standard threshold among the young adults, elderly adults, and stable COPD patients ($p<0.05$, $p<0.01$, respectively). There were significant differences in the slow walking times (<2 km/h) and fast walking times (≥2 km/h) among the young adults, elderly adults, and stable COPD patients ($p<0.01$).

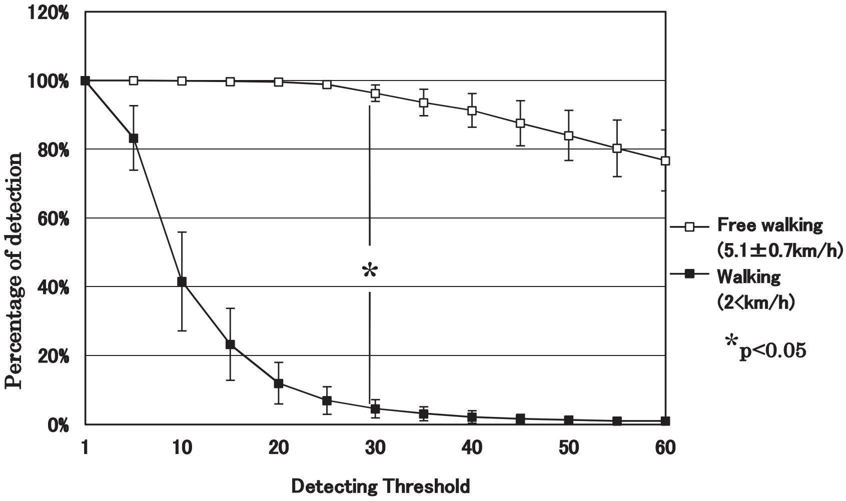

Figure 5. Percentage of detection of free walking and slow walking speed (<2 km/h) at each detection threshold.

Table 2. Daily time of each posture and movement in the three groups.

	Walking (min)	Standing (min)	Sitting (min)	Lying (min)
Young adults	151.5±49.8**[2],*[3]	66.6±31.6	458.1±86.4**[2]	43.5±44.6*[2]
Elderly adults	234.4±69.5**[1,3]	75.6±25.6	315.6±69.1**[1,3]	97.9±76.2*[1]
COPD	84.7±43.7**[2],*[1]	72.5±50.1	480.6±89.0**[2]	77.9±61.4

*, $p<0.05$; **, $p<0.01$; [1], vs young subjects; [2], vs elderly subjects; [3], vs COPD.

Table 3. Time and percentage of daily walking in the three groups.

	Walking time (<2 km/h, min)	Walking time (≥2 km/h, min)	Percentage of walking time (≥2 km/h, %)
Young adults	95.0±40.3**[2]	56.5±17.0*[2],**[3]	38.8±10.7**[3]
Elderly adults	156.5±48.0**[1,3]	77.9±34.5*[1],**[3]	32.4±9.7*[3]
COPD	69.7±37.5**[2]	15.0±11.8**[1,2]	16.6±12.1**[1],*[2]

*, p<0.05; **, p<0.01; [1], vs young adults; [2], vs elderly adults; [3], vs COPD.

There were also significant differences in the percentage of the fast walking times (≥2 km/h) among the young adults, elderly adults, and stable COPD patients (p<0.01, p<0.05, respectively).

Discussion

We assessed walking times in daily living by dividing "slow walking" and "fast walking" using our activity monitoring and evaluation system (A-MES™) triaxial accelerometer sensor as the primary objective of the study. The participants walked at 2, 3, 4 and 6 km/h, and we obtained three-dimensional accelerometer data during their walking. When this data was transformed in a computer program, 2 km/h was set as the threshold of the accelerometer sensor signal to discriminate between "slow walking" and "fast walking." When the threshold for walking was 30 times greater than the standard threshold, "walking at ≥2 km/h" was 95% and "walking at <2 km/h" was 5%, suggesting that the discrimination of acceleration signals by the accelerometer sensor was limited.

Recent developments have made it possible to analyze posture and movement, including lying, sitting, standing and walking, using the triaxial accelerometer [7, 8]. However, the measurement of walking has been limited to total walking time, and walking time by speed has not been analyzed [7, 8]. The present study is the first to distinguish between walking at <2 km/h and walking at ≥2 km/h by analyzing data with different thresholds of accelerometer sensor signals. In daily life, walking at <2 km/h accounts for most walking during personal care, whereas walking at ≥2 km/h accounts for most walking during traveling [16, 17]. Therefore, measurement by discriminating between walking at <2 km/h and walking at ≥2 km/h with the new assessment system is very useful for specifically assessing walking, the leading activity in daily life, by exercise intensity.

Previous studies have reported that the faster the walking speed is, the greater the physical intensity is, and that the metabolic equivalents (METs) quantifying physical activity levels increase relative to the walking speed [18−20]. The results of these studies suggest that walking at <2 km/h and walking at ≥2 km/h are roughly equivalent to 1−2 METs and 3−4 METs, respectively. Since 1 MET is equivalent to oxygen consumption of 3.5 mL/min/kg, daily energy expenditure can be indirectly measured by the triaxial accelerometer, and this can be used as a new measure for pulmonary rehabilitation and other clinical practice, by incorporating the conversion equation from walking speed to METs and the prediction equation of energy expenditure at rest into the analytical software program of the assessment system.

Next, we measured total daily walking time, walking time at <2 km/h and walking time at ≥2 km/h in the healthy young adults, healthy elderly adults, and COPD patients. We found that the walking time at <2 km/h was greater as a part of the total daily walking time in all three groups. The walking times at ≥2 km/h in the COPD patients, whose respiratory function was significantly decreased, were significantly shorter than those in the healthy young adults and healthy elderly adults. A plausible reason for this finding is that daily motions boost metabolism with resulting hyperventilation in the COPD patients, suggesting that shortening the fast walking times may save energy expenditure [21].

We also found that the total walking time in the healthy elderly adults was significantly longer than that in the healthy young adults. The majority of the young subjects in this study engaged in physical activities mostly at times other than the periods of physically restricted time at school and sitting at their desk for study. Since more restricted time means less leisure time, it might be difficult for young subjects to spare time for exercise including walking [21]. Also, the healthy elderly adults attended community center activities, suggesting that they might have had higher motivation for exercise. These factors may have significantly increased the total walking time in the healthy elderly adults in this study.

The analyses with different thresholds of accelerometer sensor signals in the A-MES™ terminals set by the computer enabled us to distinguish between walking at <2 km/h and walking at ≥2 km/h for the first time. The results revealed that walking at <2 km/h accounted for a majority of daily walking. In this study, however, it was difficult to distinguish walking speed at ≥2 km/h with a phase approach. More specific differentiation of faster walking speeds is needed in future studies.

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