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REGULAR ARTICLE

Development of a new instrument for evaluating leg motions using acceleration sensors (II)

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Abstract

Objective The purpose of this study was to investigate the characteristics of the average acceleration of elderly people during walking.

Method The subject cohort comprised nine men and 21 women aged ≥63 years. Subjects walked a 10-m straight course (walk test) which required stepping over six obstacles (hurdle walk test). The average acceleration was calculated from the accelerograms. Functional reach test scores and the Tokyo Metropolitan Institute of Gerontology (TMIG) index of competence, fall risk assessment, fall experience within the last year, and carelessness were used as standard indices to estimate the dynamic postural movement and fall risk.

Results The average acceleration during the walk test was not significantly correlated with the standard indices. The average accelerations at the lumbar and knee positions clustered with fall experience and carelessness, while those at the ankle and toe positions clustered with the hurdle walk test, TMIG index of competence, and fall risk assessment. Between the high- and low-risk groups classified by the conventional indices, there was a significant difference in the average acceleration at some measurement positions. The receiver operating characteristic analysis showed the possibility to discriminate the high-risk group according to the standard indices with average acceleration.

Conclusions The average acceleration during walking may be a composite index that encompasses standard indices and discriminate the high-risk group. As such, it may be a useful tool to estimate the dynamic postural movement and fall risk at all measurement positions.

Keywords Leg motion · Three-dimensional acceleration sensors · Accelerogram · Walk test · Fall risk

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Introduction

An instrument for evaluating leg motions using three-dimensional (3D) acceleration sensors was reported in an earlier publication by our group [1, 2]. This new instrument allowed us to measure leg motions during physical fitness activities without subjecting the subjects to any physical burden. Based on the results of our analysis, we then suggested that acceleration during physical fitness activities may reflect the muscle power of the legs and movement coordination and that it may be used as a new index for evaluating leg motions during dynamic postural movement, such as physical fitness activities.

Since falls often occur while walking, it is necessary to measure the momentary postural movement during walking with accuracy [3–5]. The key feature of the new instrument is its ability to measure leg motions at four points simultaneously. As a result, this instrument may enable movement coordination of dynamic postural movement to be measured during walking. However, information on the average acceleration during walking is currently lacking.

The aim of this study was to establish the validity of average acceleration as one of the indices of the dynamic postural movement. We investigated the characteristics of accelerations during the walk test and hurdle walk test and attempted to clarify the relationship of average accelerations to the indices used for evaluating the dynamic postural movement and fall risk.

Materials and methods

Subjects

The study cohort comprised 30 participants (9 men, 21 women) aged ≥63 years. Of the nine men, two were aged 65–74 years and seven were 75–84 years old; of the 21 women, one was aged 63–64 years, ten were 65–74 years old, eight were 75–84 years old, and one was aged ≥85 years. None of the participants had leg diseases or difficulty in performing the usual activities of daily living (ADL).

Public health nurses in a health center explained the outline of this study to the subjects beforehand. The researcher in charge explained the aims and methods of the study, the protection of individual information, and the possibility of removing oneself from the study with an oral explanation and by providing documents on the chosen day. Those who agreed to participate were asked to provide written informed consent. This study was approved by the Ethical Committee of Wakayama Medical University.

Methods

A representation of the measuring system is shown in Fig. 1. The measuring system comprises acceleration sensors (MA3-10Ac; MicroStone, Japan), a data logger, a data reader, and a personal computer. Four 3D acceleration sensors were placed on the body surface at the lumbar, knee, ankle, and toe positions. The three axes of the acceleration sensor are back–forward (B–F), right–left (R–L), and up–down (U–D) with the subject in a standing position. These directions, however, change depending on the position of the body during movements because the measuring directions of the sensors are originally fixed at mutually vertical positions. The data logger can accumulate 12 output signals from four sensors for about 20 min with a 10-ms time interval. The accumulated data in the EEPROM (electrically erasable and programmable read-only memory) in the data logger is transferred through a data reader to a personal computer by RS232C. The area of acceleration is integrated using the trapezoidal rule and then the integrated value is divided by measured time to obtain the average acceleration. A detailed explanation of the measuring system has been reported previously [1].

This average acceleration does not directly show muscle power of the legs or the movement coordination because the accelerogram only shows instantaneous leg motions.

Subjects walked the 10-m straight course (walk test) which included stepping over six obstacles (W10 × L50 × H20 cm^3) separated by 1.5 m (hurdle walk test). A schematic diagram of the walk test and hurdle walk test is shown in Fig. 2. The subjects were given no instructions on walking speed or style.

As standard indices, we used the results of the functional reach test (FRT) [6, 7], hurdle walk test [8, 9], the Tokyo Metropolitan Institute of Gerontology (TMIG) index of competence [10], fall risk assessment [11], fall experience within 1 year (fall experience), and the answer to the question: "Are you careless?" (carelessness).

The result of the FRT was the maximum distance that an individual could reach forward while standing and

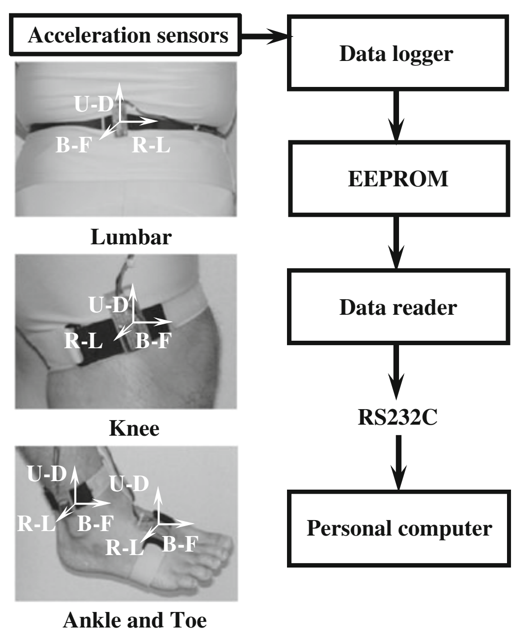

Fig. 1 Representation of the measuring system for leg motions. *EEPROM* Electrically erasable and programmable read-only memory, *B–F* back–front, *R–L* right–left, *U–D* up–down

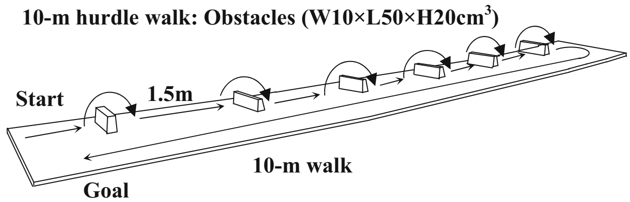

Fig. 2 Schematic diagram of the 10-m straight course (walk test) and hurdle walk test

maintaining a fixed base support [6, 7], and that of the hurdle walk test was the time the individual took to complete the hurdle walk test [8, 9].

The indices, TMIG index of competence [10], fall risk assessment [11–13], fall experience, carelessness were assessed in the questionnaire.

Statistical analyses

Although there are significant differences in the average acceleration between sexes, we evaluated data from the combined group since our aim was to establish the validity of average accelerations for indices of the dynamic postural movement and fall risk.

Student's *t* test was used to evaluate the differences in the means between the walk test and hurdle walk test, and between high- and low-risk groups. The Spearman rank correlation was calculated to assess the correlation among average acceleration, FRT, hurdle walk test, TMIG index of competence, and fall risk assessment. In all analyses, the level of statistical significance was set at 0.05. The cluster analysis was used to identify the dissimilarity with items examined in this study. Receiver-operating characteristic (ROC) analysis was used to estimate the discrimination of an individual in the high-risk group based on the standard indices with the average acceleration. We calculated the area under the curve (AUC) as the index. Since the AUC is a portion of the area of the unit square, its value varies between 0 and 1.0.

Statistical analysis was carried out using R 2.10.0 for Windows® Project for Statistical Computing; R Foundation for Statistical Computing, Vienna, Austria.

Results

The measuring time used by the new measuring system was about 5 min. No one complained about the measuring activities.

We calculated the mean and standard deviation (SD) of the average acceleration at all sensor positions during the walk test and hurdle walk test. The results are shown in Fig. 3. There were no significant differences in the means between the walk test and hurdle walk test. We then used the average acceleration value during the walk test for further analysis.

The Spearman rank correlation coefficient between average acceleration, FRT, hurdle walk test, TMIG index of competence, and fall risk assessment, respectively, is shown in Table 1. A significant correlation was obtained between FRT and the hurdle walk test, and between the TMIG index of competence and fall risk assessment. Average acceleration was not significantly correlated to the standard indices.

The results of the cluster analysis are shown in Fig. 4. Three groups appeared in the cluster analysis: (1) the average acceleration at the lumbar position on the B–F and U–D axes and at the knee position on all axes clustered with fall experience and carelessness; (2) the average acceleration at the lumbar position on the R–L axis and at the ankle and toe positions on all axes clustered with the hurdle walk test, TMIG index of competence, and fall risk assessment; (3) FRT appeared in a separate cluster from other conventional indices.

Subjects were divided into two groups based on the results of the different tests. For the FRT, the high-risk group comprised individuals whose results were <20 cm ($n = 6$), and the low-risk group comprised those individuals whose results were ≥20 cm ($n = 24$). For the hurdle walk test, the high-risk group were those individuals who took

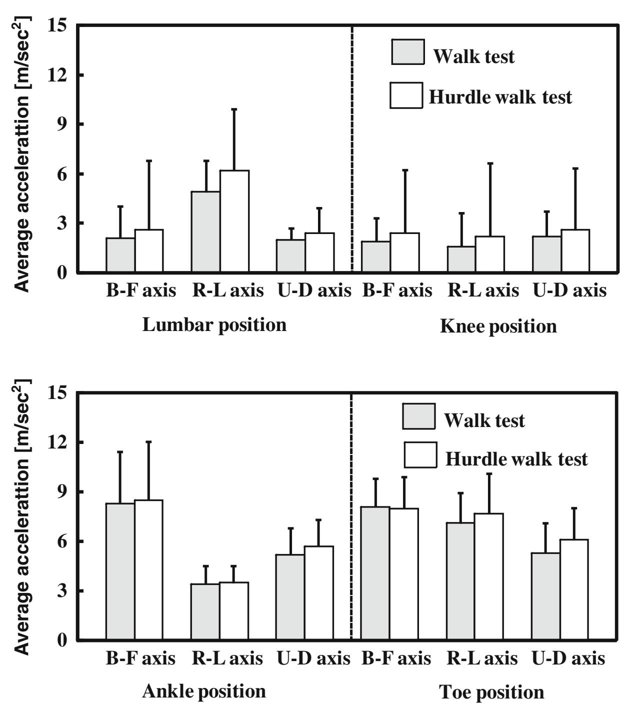

Fig. 3 Means and standard deviation of average accelerations at all sensor positions during the walk test and hurdle walk test

Table 1 Correlation coefficient between average acceleration, FRT, hurdle walk test, TMIG index of competence, and fall risk assessment, respectively

Position	Axes/direction of the acceleration sensor	FRT	Hurdle walk test	TMIG index of competence	Fall risk assessment
Lumbar	B–F axis	0.216	−0.134	0.037	0.180
	R–L axis	0.202	−0.069	−0.144	0.141
	U–D axis	0.204	−0.083	−0.074	0.123
Knee	B–F axis	0.194	−0.191	−0.240	−0.193
	R–L axis	0.299	−0.273	−0.095	0.293
	U–D axis	0.322	−0.355	−0.293	0.051
Ankle	B–F axis	0.183	−0.252	0.021	0.034
	R–L axis	0.126	−0.313	0.123	0.228
	U–D axis	0.177	−0.068	0.007	−0.068
Toe	B–F axis	−0.120	−0.014	−0.127	−0.098
	R–L axis	−0.120	−0.014	−0.127	−0.098
	U–D axis	0.119	−0.050	−0.270	−0.216
FRT			−0.450*	−0.195	−0.143
Hurdle walk test				0.102	0.000
TMIG index of competence					0.549**

* $P < 0.05$, ** $P < 0.01$

FRT Functional reach test, *TMIG* Tokyo Metropolitan Institute of Gerontology, *B–F* back–front, *R–L* right–left, *U–D* up–down

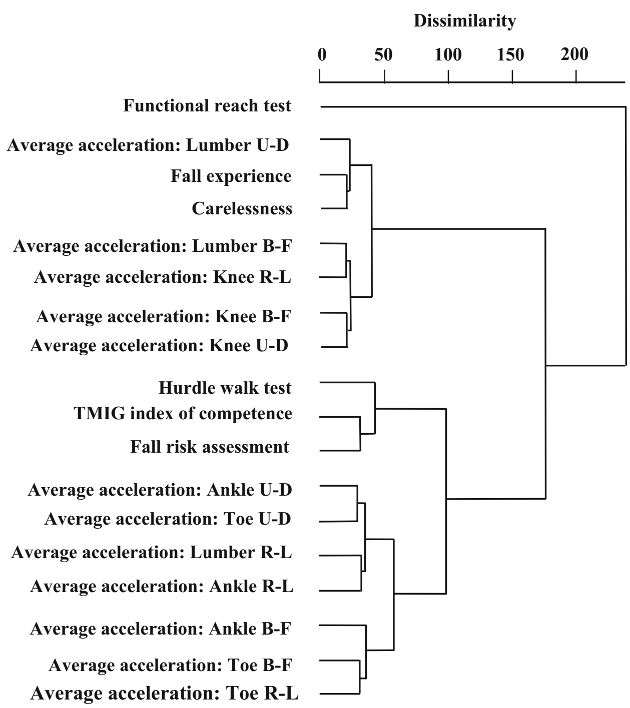

Fig. 4 Dendrogram of average acceleration at all points during walk, FRT, hurdle walk test, TMIG index of competence, fall risk assessment, fall experience, and carelessness

longer than 10 s (n = 14), while individuals in the low-risk group took ≤10 s (n = 16). By the TMIG index of competence, the high-risk group comprised individuals with ≤10 points (n = 6), and the low-risk group of individuals with ≥11 points (n = 24). By fall risk assessment, individuals in the high-risk group had ≤10 points (n = 6) and those in the low-risk group had ≥11 points (n = 24). By fall experience, the high-risk group (yes) comprised seven persons and the low-risk group (no) 23 persons. By carelessness, the high-risk group (yes) consisted of eight persons, and the low-risk group (no) of 22 persons.

We calculated the means and SD of average acceleration at all sensor positions during the walk test by high- and low-risk groups. The results are shown in Table 2. In the case of the high-risk group according to the FRT, the average acceleration at the lumbar position on the R–L axis was significantly lower than that in the low-risk group. In the case of the risk classification of individuals according to the hurdle walk test, the average acceleration at the ankle position on the B–F axis was lower in the high-risk group than in the low-risk group. In case of classification by fall experience, the average acceleration at the lumbar position on the R–L axis and U–D axis was lower in the high-group than in the low-risk group. In case of classification by carelessness, the average acceleration at the lumbar position on R–L axis was lower in the high-risk group than in the low-risk group.

We calculated the AUC for ROC analysis to estimate the discrimination of the average acceleration to high- and low-risk groups classified by the conventional indices. These results are shown in Table 3. The AUC was high (>0.650): (1) at the lumbar position on the R–L axis and U–D axis and at the knee position on the B–F axis and R–L axis when the groups were classified by FRT; (2) at the ankle position on the R–L axis when the groups were classified by the hurdle walk test; (3) at the lumbar position on the B–F axis when the groups were classified by the fall risk assessment; (4) at the lumbar position on the R–L axis and U–D axis and at the knee position on the R–L axis when the groups were classified by fall experience; (5) at

Table 2 Means and standard deviations of average acceleration at all points during walk by high and low risk groups classified by the standard indices

Standard indices	Location	B–F axis		R–L axis		U–D axis	
		High risk	Low risk	High risk	Low risk	High risk	Low risk
FRT	Number of subjects: high risk group 6, low risk group 24						
	Lumbar	1.8 ± 0.4	2.1 ± 2.1	3.9 ± 0.5*	5.1 ± 2.0	1.8 ± 0.9	2.1 ± 0.6
	Knee	1.5 ± 0.7	2.0 ± 1.6	1.1 ± 0.2	1.8 ± 2.2	1.8 ± 0.5	2.3 ± 1.6
	Ankle	7.6 ± 2.4	8.4 ± 3.3	3.9 ± 1.5	3.3 ± 1.0	5.1 ± 1.7	5.3 ± 1.6
	Toe	8.5 ± 1.8	7.9 ± 1.8	6.8 ± 1.6	7.9 ± 1.8	4.9 ± 1.7	5.3 ± 1.9
Hurdle walk test	Number of subjects: high-risk group 14, low-risk group 16						
	Lumbar	1.7 ± 0.4	2.5 ± 2.7	4.6 ± 1.6	5.2 ± 2.2	2.1 ± 0.8	1.9 ± 0.5
	Knee	1.6 ± 0.5	2.3 ± 2.0	1.2 ± 0.4	2.1 ± 2.8	1.8 ± 0.4	2.6 ± 2.1
	Ankle	7.1 ± 2.5*	9.5 ± 3.4	3.2 ± 1.1	3.8 ± 1.0	5.2 ± 1.9	5.3 ± 1.3
	Toe	8.0 ± 1.7	8.1 ± 1.9	6.5 ± 1.6	7.6 ± 1.8	5.0 ± 1.6	5.5 ± 2.1
TMIG index of competence	Number of subjects: high-risk group 6, low-risk group 24						
	Lumbar	1.5 ± 0.5	2.2 ± 2.1	4.7 ± 1.7	5.0 ± 1.9	2.0 ± 0.8	2.0 ± 0.7
	Knee	1.6 ± 0.5	2.0 ± 1.6	1.1 ± 0.3	1.8 ± 2.2	1.8 ± 0.4	2.3 ± 1.6
	Ankle	8.8 ± 3.6	8.1 ± 3.1	3.5 ± 1.5	3.4 ± 1.0	4.8 ± 2.3	5.4 ± 1.5
	Toe	8.4 ± 1.7	8.0 ± 1.8	6.3 ± 0.9	7.2 ± 1.9	5.6 ± 1.5	5.2 ± 1.9
Fall risk assessment	Number of subjects: high-risk group 6, low risk-group 24						
	Lumbar	1.5 ± 0.4	2.2 ± 2.1	4.5 ± 1.8	5.0 ± 1.9	2.0 ± 0.6	2.0 ± 0.7
	Knee	1.8 ± 0.5	1.9 ± 1.6	1.2 ± 0.3	1.8 ± 2.2	1.9 ± 0.5	2.2 ± 1.6
	Ankle	7.8 ± 3.6	8.4 ± 3.1	3.2 ± 1.6	3.5 ± 1.0	6.0 ± 2.5	5.1 ± 1.3
	Toe	8.7 ± 2.4	7.9 ± 1.6	6.9 ± 1.5	7.1 ± 1.8	6.0 ± 2.1	5.1 ± 1.7
Fall experience	Number of subjects: high-risk group 7, low-risk group 23						
	Lumbar	1.8 ± 0.4	2.2 ± 2.2	3.7 ± 0.4**	5.3 ± 2.0	1.5 ± 0.1**	2.2 ± 0.7
	Knee	2.1 ± 0.8	1.8 ± 1.6	1.0 ± 0.2	1.8 ± 2.2	1.9 ± 0.4	2.3 ± 1.7
	Ankle	8.5 ± 2.7	8.2 ± 3.3	3.2 ± 0.8	3.5 ± 1.2	5.9 ± 2.4	5.0 ± 1.3
	Toe	9.7 ± 0.7	7.5 ± 1.6	6.8 ± 0.5	7.1 ± 2.0	5.8 ± 1.3	5.1 ± 2.0
Carelessness	Number of subjects: high-risk group 8, low-risk group 22						
	Lumbar	1.7 ± 0.3	2.2 ± 2.2	3.9 ± 0.5**	5.2 ± 2.1	1.9 ± 0.6	2.0 ± 0.7
	Knee	1.4 ± 0.3	2.1 ± 1.6	1.2 ± 0.3	1.8 ± 2.3	1.7 ± 0.4	2.3 ± 1.4
	Ankle	8.7 ± 3.6	8.1 ± 3.0	3.7 ± 1.7	3.4 ± 0.9	5.0 ± 1.1	5.3 ± 1.8
	Toe	7.1 ± 1.1	8.3 ± 1.9	7.8 ± 1.9	6.8 ± 1.6	4.8 ± 1.8	5.4 ± 1.8

* $P < 0.05$, ** $P < 0.01$ (high-risk group vs. low-risk group)

the knee position on the U–D axis when the groups were classified by carelessness.

Discussion

In this study, we used a new instrument to measure average acceleration during the walk test and hurdle walk test—without receiving any complaints, even in the aged group. We investigated the relationship of acceleration during the walk test to the conventional indices of dynamic postural movement and fall risk.

The average acceleration during the walk test was not significantly correlated, according to the Spearman rank coefficient, to FRT, the hurdle walk test, TMIG index of competence, and fall risk assessment. This lack of correlation indicates that average acceleration at a position on one axis has no specific characteristics to correlate with these four indices.

The values for average acceleration were divided into two clusters. Those at the lumbar position and knee position clustered with fall experience and carelessness, while those at the ankle position and toe position clustered with the hurdle walk test, TMIG index of competence, and fall risk assessment.

Fall experience easily leads to muscle weakness and a reduced range of joint motion due to the anxiety associated with falling [14]. Carelessness relates to a low self-efficacy

Table 3 The area under the receiver operator characteristic curve to discriminate the high- and low-risk groups classified by the standard indices

Standard indices	Location	B–F axis	R–L axis	U–D axis
FRT	Lumbar	0.514	0.653	0.701
	Knee	0.660	0.722	0.625
	Ankle	0.500	0.382	0.486
	Toe	0.306	0.521	0.507
Hurdle walk test	Lumbar	0.549	0.487	0.460
	Knee	0.558	0.554	0.647
	Ankle	0.625	0.705	0.563
	Toe	0.415	0.616	0.473
TMIG index of competence	Lumbar	0.625	0.458	0.542
	Knee	0.500	0.604	0.556
	Ankle	0.375	0.479	0.646
	Toe	0.361	0.611	0.347
Fall risk assessment	Lumbar	0.653	0.563	0.500
	Knee	0.313	0.576	0.417
	Ankle	0.528	0.632	0.389
	Toe	0.403	0.486	0.292
Fall experience	Lumbar	0.497	0.801	0.795
	Knee	0.242	0.770	0.485
	Ankle	0.385	0.522	0.441
	Toe	0.745	0.460	0.335
Carelessness	Lumbar	0.534	0.619	0.648
	Knee	0.500	0.591	0.682
	Ankle	0.415	0.511	0.483
	Toe	0.585	0.296	0.568

to present falls, such as anxiety disorder [15, 16]. Consequently, this cluster, which includes fall experience and carelessness, reflects the functionality of, for example, muscle power and range of motion. The average acceleration at the lumbar and knee positions thus indicates walking ability.

The hurdle walk test is affected by balance ability [17]. The TMIG index of competence and fall risk assessment are related to the maintenance of physical fitness [18]. This cluster, which includes the hurdle test, TMIG index of competence and fall risk assessment, thus reflects balance ability and ADL. The average acceleration at the ankle and toe positions reflects the coordination needed to maintain the ability of dynamic postural balance and ADL.

FRT is the index related to dynamic and static postural balance ability [19, 20]. The center of foot pressure through the muscles and hip joints for attitude dynamics and control in the aged group was different from that in the young group. As a result, FRT in the aged seems to include the risk factor for falls, with the exception of ability of dynamic postural balance [21]. In our study, the average acceleration showed high dissimilarity to FRT.

The average acceleration includes conventional indices to estimate the dynamic postural movement and fall risk, except for FRT. Thus, the average acceleration at all positions on all axes may be a composite index that packages the conventional indices. We found that the average acceleration shown by the high- and low-risk groups was significantly different when classified by the conventional indices. The average acceleration in the high-risk group at the lumbar position was significantly lower than that in the low-risk group when classified by fall experience and carelessness. These results are associated with a decline in walking ability since muscle weakness leads to significant postural instability as well as inactivity in daily life [22]. The average acceleration at the lumbar position in the aged group was higher than that in the young group due to trunk instability in the former [23]. However, as a result of a further decline in walking ability in the high-risk group, the average acceleration might become lower in the low-risk group.

The aged walk with a flat-footed action because of muscle weakness of the lower leg and show poor coordination during walking [24]. The average acceleration at the toe position was therefore higher in the aged group than in the young group [23]. However, as a result of further reduced coordination due to advanced muscle weakness, the average acceleration in the high-risk group was lower than in the low-risk group.

The average acceleration in the high-risk group at the lumbar position during the walk test was significantly lower than that in the low-risk group when classified by FRT. Although FRT is a valid index to estimate the dynamic postural movement in a young group [25, 26], FRT in the aged is assumed to be different from that in the young group. The elderly use more hip movements to maintain the body equilibrium [27, 28], while the young use ankle movements. Because of this strategy [23], the average acceleration at the lumbar position in the aged group was higher than that in the young group. However, in the high-risk group, the instant movement of the hip joint is not able to be used for body equilibrium because of advanced muscle weakness and, consequently, the average acceleration at the lumbar point was lower in the high-risk group than in the low-risk group.

The results of the ROC analysis show that average acceleration at the ankle position may screen the high-risk group classified by the hurdle walk test, that average acceleration at the lumbar and knee positions may screen group by fall experience and carelessness, and that average acceleration at the lumbar and knee positions may screen groups by FRT. The hurdle walk test had a low dissimilarity to the average accelerations at the ankle and toe positions. The average acceleration at the ankle position was able to discriminate the high-risk group classified by the hurdle walk test. Fall experience and carelessness had a low dissimilarity to the average accelerations at the lumbar and knee positions. The average accelerations at the lumbar and knee positions were able to discriminate the high-risk groups classified by fall experience and carelessness. In the case of FRT, the average acceleration at the lumbar position was significantly lower in the high-risk group than in the low-risk group. The average acceleration at the lumbar position was able to discriminate the high-risk group classified by FRT. However, the reason why the average acceleration at the knee position was able to discriminate the high-risk group classified by FRT is unknown.

We calculated the root mean square of three axes to estimate the total effects and found that the results agreed with those using 12 measurement points, with the exception of the AUC for the ROC analysis. The AUC values at the lumber position to discriminate to the high-risk group classified by fall risk assessment and at the knee position to discriminate to the high-risk group classified by fall experience using root mean square were lower than those using the 12 measurement points; for these measures calculation of the root mean square had no total effect. We therefore used the data of average acceleration at the 12 measurement points.

The measuring system introduced here is hassle free with respect to subject involvement and is a convenient tool by which researchers can measure average acceleration, even among the elderly. This system may enable the dynamic postural movement and fall risk to be measured by assessing the overall rating of average acceleration at the lumbar, knee, ankle, and toe positions and to discriminate the risk group. Consequently, the average acceleration may be a useful measure to estimate the dynamic postural movement and fall risk by means of any measurement position simultaneously in one measurement.

There were no significant differences in male–female distribution between the high- and low-risk groups, with the exception of the hurdle walk test, and no significant differences in mean age, except for FRT. However, there was an insufficient number of subjects to estimate the influence of differences in male–female distribution and mean age between the high- and low-risk groups. We therefore used the combined group of men and women in this study. Further study is necessary to clarify the influences of sex distribution and age variation.

Functional asymmetry in both lower extremities causes a fall, and this should be taken into consideration to prevent falls. Future assessment of the differences in acceleration between the left and right lower limbs is required.

In conclusion, we measured that the average acceleration, based on accelerograms, of 30 subjects aged $\geq$63 years during the walk test. The Spearman rank correlation was not significant in terms of the conventional indices for evaluating the dynamic postural movement and fall risk, which indicates that the average acceleration at one axis at a position has no specific characteristics to correlate with the standard. Average acceleration was divided into two clusters: accelarations at the lumbar and knee positions clustered together with fall experience and carelessness; accelerations at the ankle and toe positions clustered with the hurdle walk test, TMIG index of competence, and fall risk assessment. Average acceleration may be a composite index that encompasses the standard indices. There was a significant difference in the average acceleration at some measurement positions between high- and low-risk groups classified by conventional indices. The average acceleration has the possibility to discriminate the high-risk group classified by the standard indices. As such, it may be a useful tool to estimate the dynamic postural movement and fall risk by means of all measurement positions.

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