Functional Fitness Test

Calf girth and functional fitness variables including usual and maximum walking speeds and knee extension strength were measured. In measures of walking speed, participants were allowed to use assistive walking devices only if they expressed strong concerns about walking without a device or if there was any danger of falling. The knee extension strength measurement was taken twice, and the higher value divided by body weight (Nm/kg) were analyzed. The procedures for the functional fitness tests have been described in detail in previous reports.[19,20]

Intervention

Exercise

A comprehensive physical fitness and muscle mass enhancement training program of moderate intensity was provided for the participants in the exercise groups. The exercise intervention consisted of 60-minute exercise sessions held at the TMIG twice per week for 3 months. Each exercise intervention group was divided into two subgroups, with participants exercising together within their assigned group in one of four exercise sessions offered per day.

Each exercise session consisted of a 5-minute warm-up, 30 minutes of strengthening exercise, 20 minutes of balance and gait training, and 5 minutes of cool down. The strengthening exercises were performed in a progressive sequence from seated to standing positions. For each type of exercise, participants were instructed to complete up to eight repetitions of the movements. When the exercises were properly executed without significant fatigue or loss of proper execution, the resistance was increased. The progressive resistance was provided through the use of resistance bands or ankle weights. Intensity was maintained at approximately 12 to 14 on the Borg Rate of Perceived Exertion scale.[21] The principal investigator, along with the exercise instructor and assistant trainers, assessed each individual's ability to increase intensity.

Chair exercise: The chair-seated exercises were used in the early stages of the program because the participants were frail older adults and it provided a secure and stable position. Repetitions of toe raises, heel raises, knee lifts, knee extensions, and others were performed while seated on a chair. Hip flexions, lateral leg raises, and repetitions of other exercises were performed standing upright behind the chair and holding the back of the chair for stability.

Ankle-weight exercise: To strengthen lower extremities, a fixed weight was placed on the ankle while participants performed strengthening exercises. Weights of 0.50, 0.75, 1.00, and 1.50 kg were prepared and used in accordance with each participant's strength level as the resistance progressively increased. The exercises performed using these ankle weights included seated knee flexion and extension and standing knee flexion and extensions.

Exercises using a resistance band: Resistance bands were used to strengthen the upper and lower body. Lower body exercises included leg extension and hip flexion. Upper body exercises included double-arm pull downs and biceps curls.

Balance and gait training: The balance training was focused on improvement of static, dynamic, and lateral balancing ability. Exercises included standing on one leg, multidirectional weight shifts, tandem stand, and tandem walk. Participants practiced proper gait mechanics that focused on the maintenance of stability during walking and increasing stride length, toe elevation of the forward limb, heel elevation of the rear limb, frequency of stepping, and heel–floor angle. Exercises included raising the toes (dorsiflexion) during the forward swing of the leg, kicking off the floor with the ball of the foot, walking with directional changes, and gait pattern variations.

Amino Acid Supplementation

Essential AAS was provided for the participants in the AAS groups every 2 weeks. Packets of powdered amino acid supplements (42.0% leucine, 14.0% lysine, 10.5% valine, 10.5% isoleucine, 10.5% threonine, 7.0% phenylalanine, and 5.5% other) were provided for the participants to be taken with water or milk, and they were instructed to take the 3-g supplement two times a day (6 g daily) every day for 3 months.[22] To monitor their amino acid intake accurately, participants were given record sheets that were collected every 2 weeks on which they recorded what time of day they took the supplement and the amount of amino acid taken every day.

Health Education

Participants in the HE group took a class once a month for 3 months, a total of three times. The classes focused on cognitive function, osteoporosis, and oral hygiene. Participants were asked to continue their regular lifestyle habits, and no specific instructions on diet or physical activity were given.

Data Analysis

Sample size calculations using univariate one-factor repeated-measures analysis of variance (ANOVA) to examine significant differences in means at baseline and after the 3-month intervention ($\alpha = 0.05$, power = 0.80) with an effect size of 0.15 required a sample size of 28 participants. Esimating a potential attrition rate of 25%, 38 subjects per group were required.[23] One-way ANOVA was used to test any differences in baseline measures and percentage changes between groups, and chi-square tests were performed on categorical variables. Percentage changes in muscle mass and functional fitness after the intervention were calculated using the following formula: % change = ((postintervention value–baseline value)/(baseline value) × 100). Two-way repeated-measures ANOVA was used to evaluate the differences in the effect of the intervention on the outcome measures between groups, and a post hoc test was done on variables showing significant differences to determine which groups were different. Multiple logistic regressions were performed to compare the effects of the four intervention groups on each outcome variable after 3 months of intervention. All analyses were performed using SPSS version 15.0 of Windows (SPSS, Inc., Tokyo, Japan).

RESULTS

The baseline demographic, fitness, and interview variables of the participants in the four groups are summarized in Table 1. All of the baseline characteristics were similar between the groups.

The mean attendance rates during the 3-month intervention were 70.3% in the exercise + AAS group, 80.5% in the exercise group, 72.2% in the AAS group, and 71.8% in the HE group. Eleven participants (exercise + AAS = 4, exercise = 3, AAS = 2, HE = 2) were unable to complete the study after randomization because of spouse care (n = 3), admission to nursing home (n = 2), lack of motivation (n = 2), severe knee or back pain (n = 1), death (n = 1), falls and hip fracture (n = 1), and hospitalization (n = 1; Figure 2).

In comparing the pre- and postintervention changes in body composition and functional fitness of the groups (Table 2), there was a significant group × time interaction for leg muscle mass ($F = 4.253$, $P < .007$; exercise + AAS > HE), usual and maximum walking speeds (exercise and exercise + AAS > HE), and knee extension strength ($F = 3.558$, $P = .02$; exercise + AAS > HE).

The within-group analysis showed significant changes in leg muscle mass in the exercise + AAS ($P < .001$) and exercise ($P = .005$) groups and changes in usual walking speed in the exercise + AAS ($P = .001$), exercise ($P < .001$), and AAS groups ($P = .01$). Knee extension strength improved significantly only in the exercise + AAS group ($P = .01$), no improvement was seen in exercise or AAS, and a statistically significant decrease was observed in the HE group ($P = .02$; Figure 1).

Table 3 shows the effects of the type of intervention on changes in combined variables of muscle mass and physical function. Significant increases in leg muscle mass and knee extension strength (odds ratio (OR) = 4.89, 95% confidence interval (CI) = 1.89–11.27) and leg muscle mass and usual walking speed (OR = 4.11, 95% CI = 1.33–13.68) were observed in only the exercise + AAS group.

DISCUSSION

Although many definitions of sarcopenia have been reported,[1–3,24] there has recently been a focus not only on the loss of appendicular skeletal muscle mass, but also on functional decline.[25] In this study, sarcopenic women were operationally defined based on declines in muscle strength or walking ability that accompany the loss of skeletal muscle mass or low BMI. Because defining sarcopenia was beyond the scope of this study, the focus of the discussion will be on the effects of the intervention. To evaluate the intervention effects, the changes observed in the single variables as well as the combined variables will be discussed.

Many studies have focused on exercise or nutrition as interventions to reverse sarcopenia, but the results of these studies have not always been consistent.[8,9,12,26]

This study demonstrated that appendicular muscle mass and walking speed increased with the combination of exercise and essential amino acid ingestion, as well as with the separate exercise and amino acid interventions, but muscle strength improved only with the combination of exercise and amino acid ingestion.

A recently published meta-analysis[9] and a Cochrane review article also confirmed that resistance training two to three times a week can improve physical function and functional limitations and can reduce disability and muscle weakness in older people.[27] Previous studies have demonstrated that resistance training in elderly people produces

Table 1. Selected Variable Characteristics of Participants at Baseline According to Study Group

Characteristic	Exercise + AAS (n = 38)	Exercise (n = 39)	AAS (n = 39)	Health Education (n = 39)	*F*-Value*	*P*-Value*
Age, mean ± SD	79.5 ± 2.9	79.0 ± 2.9	79.2 ± 2.8	78.7 ± 2.8	0.577	.63
Height, cm, mean ± SD	147.1 ± 6.7	147.7 ± 4.4	145.8 ± 4.5	146.5 ± 4.9	0.960	.41
Body weight, kg, mean ± SD	39.5 ± 5.5	41.1 ± 4.7	40.1 ± 3.2	40.4 ± 3.9	0.874	.46
Body mass index, kg/m^2, mean ± SD	18.3 ± 2.5	18.9 ± 2.0	18.9 ± 1.6	18.8 ± 1.7	0.745	.53
Calf girth, cm, mean ± SD	18.3 ± 2.5	18.9 ± 2.0	18.9 ± 1.6	18.8 ± 1.7	0.745	.53
Lean body mass, kg, mean ± SD	29.1 ± 3.4	30.0 ± 2.6	28.8 ± 2.0	29.3 ± 2.4	1.505	.22
Muscle mass, kg, mean ± SD	26.9 ± 3.1	27.7 ± 2.3	26.5 ± 1.8	27.0 ± 2.2	1.538	.21
Appendicular muscle mass, kg, mean ± SD	13.3 ± 1.6	13.7 ± 1.3	13.1 ± 1.0	13.3 ± 1.2	1.502	.22
Legs muscle mass, kg, mean ± SD	9.8 ± 1.2	10.1 ± 1.0	9.7 ± 0.7	9.9 ± 0.9	1.570	.20
Usual walking speed, m/s, mean ± SD	1.26 ± 0.27	1.29 ± 0.28	1.29 ± 0.20	1.18 ± 0.22	1.701	.17
Maximal walking speed, m/s, mean ± SD	1.62 ± 0.37	1.67 ± 0.31	1.67 ± 0.27	1.55 ± 0.32	1.150	.33
Knee extension strength, Nm, mean ± SD	45.9 ± 11.3	46.6 ± 11.1	46.7 ± 7.8	47.4 ± 10.5	0.139	.94
Falls, %	21.1	17.9	15.4	20.5	0.519	.91
Exercise habit, %	26.3	25.6	38.5	33.3	2.029	.57
Urinary incontinence, %	44.7	38.5	41.0	25.6	3.414	.33
Osteoporosis history, %	36.8	43.6	48.7	30.8	2.987	.39
Heart disease history, %	10.5	15.4	12.8	17.9	0.977	.81
Diabetes mellitus history, %	7.9	5.1	5.1	12.8	2.156	.54

* One-way analysis of variance for continuous variables and chi-square test for categorical variables.
AAS = amino acid supplementation; SD = standard deviation.

Table 2. Comparison of Muscle Mass and Functional Fitness Variables Between Groups After 3-Month Intervention

Variable	Group	Mean ± Standard Deviation		Analysis of Variance (Group × Time), *P*-Value	Post Hoc Analysis*
		Baseline	After 3-Month Intervention		
Muscle mass, kg	Exercise + AAS	26.76 ± 2.77	27.26 ± 3.04	*F* = 1.076, .36	
	Exercise	28.09 ± 1.90	28.51 ± 2.39		
	AAS	26.25 ± 1.81	26.53 ± 2.10		
	HE	27.48 ± 2.04	27.66 ± 2.23		
Appendicular muscle mass, kg	Exercise + AAS	13.25 ± 1.35	13.59 ± 1.53	*F* = 1.354, .26	
	Exercise	13.90 ± 1.06	14.19 ± 1.33		
	AAS	12.86 ± 0.99	13.03 ± 1.10		
	HE	13.57 ± 1.16	13.67 ± 1.05		
Legs muscle mass, kg	Exercise + AAS	9.76 ± 1.01	10.07 ± 1.13	*F* = 4.253, .007	Exercise + AAS > HE
	Exercise	10.28 ± 0.81	10.53 ± 1.05		
	AAS	9.55 ± 0.73	9.65 ± 0.83		
	HE	10.14 ± 0.87	10.11 ± 0.81		
BMI, kg/m^2	Exercise + AAS	18.30 ± 2.64	18.14 ± 2.68	*F* = 0.606, .61	
	Exercise	18.80 ± 1.30	18.50 ± 1.41		
	AAS	18.84 ± 1.43	18.56 ± 1.62		
	HE	18.83 ± 1.75	18.77 ± 1.67		
Usual walking speed, m/s	Exercise + AAS	1.27 ± 0.25	1.43 ± 0.29	*F* = 4.213, .007	Exercise and Exercise + AAS > HE
	Exercise	1.31 ± 0.24	1.50 ± 0.23		
	AAS	1.30 ± 0.18	1.36 ± 0.18		
	HE	1.19 ± 0.21	1.22 ± 0.23		
Maximum walking speed, m/s	Exercise + AAS	1.64 ± 0.34	1.92 ± 0.37	*F* = 9.374, <.001	Exercise and Exercise + AAS > HE
	Exercise	1.72 ± 0.27	2.04 ± 0.27		
	AAS	1.71 ± 0.28	1.92 ± 0.27		
	HE	1.57 ± 0.31	1.64 ± 0.31		
Knee extension strength, Nm/kg	Exercise + AAS	1.15 ± 0.27	1.23 ± 0.29	*F* = 3.558, .02	Exercise + AAS > HE
	Exercise	1.12 ± 0.30	1.14 ± 0.26		
	AAS	1.15 ± 0.25	1.14 ± 0.25		
	HE	1.14 ± 0.26	1.00 ± 0.26		

* A post hoc analysis was performed using the Scheffe method.
AAS = amino acid supplementation; HE = health education; BMI = body mass index.

Table 3. Change in Leg Muscle Mass and Functional Fitness After Intervention According to Study Group

Dependent Variable*	Adjusted Odds Ratio (95% Confidence Interval)		
	AAS	Exercise	Exercise + AAS
Change in leg muscle mass and knee extension strength	1.99 (0.72–5.65)	2.61 (0.88–8.05)	4.89 (1.89–11.27)
Change in leg muscle mass and usual walking speed	1.35 (0.45–4.08)	2.41 (0.79–7.58)	4.11 (1.33–13.68)

Reference: health education.
* 1 = improve, 0 = no change or decrease.
AAS = amino acid supplementation.

9% to 15% increases in strength and approximately 5% in thigh muscle volume.[28,29] Also, many studies have shown that resistance training in elderly people must be conducted at high intensities and volumes to see improvements.[9,27] In contrast, less-intense resistance exercise programs have produced little or no strength gains.

The data in this study show improvements of 2.4% in leg muscle mass, 2.0% in appendicular muscle mass, and 4.3% in leg strength in the exercise group. The moderate-intensity exercise provided in this trial produced strength gains that were smaller than those seen in previous studies, but the combination of moderate intensity exercise and AAS increased muscle mass 3.1% and muscle strength 9.3%, gains that are comparable with those observed in previous studies of high-intensity exercise.[28]

The results of the current study showed that total muscle mass, appendicular muscle mass, and walking speed significantly increased in the exercise group, suggesting that exercise is effective in the improvement of muscle mass and functional fitness, but increases in muscle

strength were not observed. These results indicate that exercise alone is insufficient for recovery in sarcopenic elderly women.

Previous studies have indicated that declines in muscle mass are related to declines in muscle protein synthesis rates in older adults and that leucine-enriched essential amino acid mixtures are primarily responsible for the amino acid-induced muscle protein anabolism in elderly people.[11,22] These studies investigated the effects of different amino acid dosages (from 6.7 to 20.0 g/d) on protein synthesis, and the 6.0-g/d dosage provided in this study is lower than in previous studies, but the mean weights of the subjects in such studies were from 71.0 to 81.3 kg, making the dosage of amino acid between 0.090 and 0.246 g/kg of body weight. The amino acid dosage in the current study was 0.151 g/kg, which is comparable with the amounts found in the literature.[11,22,26] The results of the current study showed that muscle mass, appendicular muscle mass, and leg muscle mass significantly increased in the AAS group, which is consistent with previous findings.

Many studies have demonstrated an increase in muscle mass from nutritional supplementation, but an increase in muscle strength does not always accompany an increase in muscle mass. A recent study concluded that essential AAS alone was not sufficient to increase muscle strength.[26] Similarly, although the results of the current study showed that AAS alone increased muscle mass, improvement in muscle strength was not observed. The results of the present study showed that muscle mass increased significantly with exercise or essential AAS, although muscle strength, measured according to knee extension strength, improved significantly only in the exercise + AAS group.

Next, the discussion will focus on the changes in the combined variables. One study that investigated the effects of resistance exercise and nutritional supplementation on muscle mass and strength in older adults concluded that high-intensity resistance exercise was beneficial in increasing muscle mass and muscle strength, but the nutritional supplementation, which contained only a small percentage of a soy-based protein within a mixture of mainly carbohydrates, did not contribute to those gains.[8] As illustrated in Figure 2, exercise alone was effective in enhancing single variables such as leg muscle mass or usual walking speed. Similarly, the AAS group improved usual walking speed, but rationally, to treat sarcopenia, improvements in single variables are not sufficient. Improvements observed in the combined variables would presumably lead to the most-efficient reversal of sarcopenia. Significant improvements in the combinations of leg muscle mass, knee extension strength, and walking speed were seen only in the exercise + AAS group. Although whether exercise + AAS was better than either intervention alone remains inconclusive, these results suggest that exercise + AAS may be necessary for benefits in muscle mass and strength.

This study has several limitations. First is the measurement of body composition estimated using BIA. Although magnetic resonance imaging (MRI), computed tomography, and dual-energy X-ray absorptiometry are common, accurate clinical methods of measuring muscle mass,[30,31] they are cost ineffective and are not always appropriate for field studies. BIA is simple, noninvasive, and inexpensive and has been widely used in field studies. The comparison of MRI and BIA measurements has revealed a strong correlation between the two, confirming the validity of the BIA method for muscle mass measurement in older adults.[13,17,18] Therefore, the validity of the data collected using BIA has little influence on the interpretation of the results of this study. Second, it has been reported that AAS enhances muscle protein synthesis,[11,22,32] but the mechanism of the increase in muscle mass from AAS was not explored in the current investigation. Therefore, the results of this study were interpreted based on the assumption that muscle protein synthesis had been enhanced. Third, the effects of the exercise + AAS should have been determined with the use of placebos, but placebo treatments were not provided in this study, so future research should include placebos to observe the effects of exercise and AAS on physical function and muscle strength. Fourth, the total number of dropouts in this study was 11 people, and they were not included in the data analysis. Many studies have used intention-to-treat (ITT) analyses to determine the effects of RCTs, and the use of ITT analyses are increasing, although one previous study found that only approximately 35% of 274 RCTs used ITT analyses.[33] The current study was not an ITT analysis because it confirmed that there were no significant differences between the dropouts and the participants who completed the study, and the exclusion of the 11 dropouts from the analysis did not affect the integrity of the baseline randomization. Finally, previous research has shown that milk contains essential amino acids.[34,35] Because some of the participants took the AAS with milk, the exact essential amino acid dosage in this study could not be determined, and the effect of drinking milk on the results of this study was not confirmed. Future research should avoid the intake of milk with amino acids when investigating the effects of amino acids on muscle strength and mass and physical function.

This study demonstrated that exercise and nutrition may be necessary for the basic treatment of increasing muscle mass and strength to reverse the effects of sarcopenia in community-dwelling sarcopenic women. Exercise and AAS together have significant effects on enhancing not only muscle strength, but also the combined variables of muscle mass and walking speed and of muscle mass and strength in this study population, but further follow-up studies on larger populations are required to confirm these results.

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Author Contributions: H. Kim developed the study concept and design, recruited subjects, developed the intervention program, analyzed and interpreted the data, and prepared the manuscript. S. Takao interpreted the data and reviewed the manuscript for accuracy. K. Saito assisted in AAS and supervised the interview survey. Y. Hideyo assisted in subject recruitment, supervised the

interviewers, and interpreted the data. M. Kobayashi assisted in AAS and subject recruitment and interpreted the data. H. Kato assisted in assisted AAS and body composition assessment. M. Katayama assisted in AAS and interview survey.

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〈原　著〉

手段的日常生活活動の自立した地域在住高齢者における転倒恐怖感に関連する要因の検討

大矢　敏久[1)]　内山　靖[1)]　島田　裕之[2)]　牧迫飛雄馬[2)3)]
上井　剛彦[2)]　吉田　大輔[2)4)]　上村　一貴[1)3)]　鈴木　隆雄[5)]

要　約　**目的**：手段的日常生活活動（IADL）の自立した地域在住高齢者における転倒恐怖感の存在率及びその特徴を検討することを本研究の目的とした．**方法**：対象は，IADLの自立した地域在住高齢者119名（平均年齢75.7±7.2歳，女性60名）であった．問診により聴取した転倒恐怖感の有無により，転倒恐怖感を有している者をあり群，有していない者をなし群とした．過去1年間の転倒経験，過去1カ月における疼痛の有無，3種類以上の服薬の有無，そして慢性疾患の有無もあわせて聴取した．そして，身体活動量としてInternational Physical Activity Questionnaire：IPAQ，生活空間としてLife-Space Assessment：LSA，心理状態としてGeriatric Depression Scale：GDSを日本語版の質問紙を用いて調査した．さらに，身体機能としてTimed Up and Go test：TUG，開眼片足立ち保持時間を測定した．各指標に対する群間比較を連続変数には対応のないt検定，カテゴリー変数にはχ^2検定を用いて検討した．さらに転倒恐怖感の有無を従属変数とし，単変量解析で有意な差が認められた指標を独立変数とした多重ロジスティック回帰分析の強制投入法を用いて，転倒恐怖感に関連する要因を検討した．**結果**：転倒恐怖感を有する者は対象者全体の51.3%で，その全員が日常生活に支障はないと回答した．転倒恐怖感が，あり群ではなし群に比べ有意に女性，痛み，慢性疾患，転倒経験を有する者の割合が各々高かった．また，あり群の方が，LSAの得点が低く，TUGの所要時間が長く，開眼片足立ち保持時間が短く，各項目において有意な群間差がみられた（$p<0.05$）．多重ロジスティック回帰分析においてLSA（総得点120点）のみが転倒恐怖感の有無と有意に関連した（OR：0.96，95%信頼区間＝0.93～0.99）．**結論**：IADLが自立した地域在住高齢者の51.3%に転倒恐怖感が存在し，高い値を示した．転倒恐怖感は，多変量解析では，LSAとのみ関連があった．今後，縦断的な調査によりこの因果関係を明らかにし，効果的な介入方法を確立することが重要である．

Key words：地域在住高齢者，転倒恐怖感，生活空間

（日老医誌　2012；49：457-462）

緒　言

転倒恐怖感は，1980年代に，転倒後の心理的トラウマの結果起こるPost-fall syndromeの要素として定義された．高齢者は転倒を経験すると，再度転倒することに恐怖感をもち，移動の際，過度に注意を払い歩くようになる[1)]．一方で，転倒経験のない高齢者にも転倒恐怖感が存在することが明らかとなり新たな定義が1990年にTinettiらによって提唱された[2)]．それは「ある活動を行う機能は保たれているにもかかわらず，それを避けるように働く転倒に対する不安」というものであり，日常生活活動に支障を来たす恐怖感として定義された．その後転倒恐怖感の存在率やその発生に関係する因子を同定する研究が多くなされてきた．

2008年に報告されたSystematic reviewによると，転倒恐怖感は地域在住高齢者の21～85%に存在すると報告されている[3)]．転倒恐怖感の発生に関係する因子は，最も多く報告されているものが過去の転倒経験[1,5)]であった．また，加齢や女性であることなどの基本属性[6,7)]，慢性疾患の既往歴，服薬，疼痛などの健康状態[6,7)]，歩行，バランス機能低下[8)]，抑うつや不安などの心理状態[9,10)]が

1）T. Oya, Y. Uchiyama, K. Uemura：名古屋大学大学院医学系研究科リハビリテーション療法学専攻理学療法学分野
2）H. Shimada, H. Makizako, T. Doi, D. Yoshida：国立長寿医療研究センター認知症先進医療開発センター在宅医療・自立支援開発部自立支援システム開発室
3）H. Makizako, K. Uemura：日本学術振興会
4）D. Yoshida：長寿科学振興財団
5）T. Suzuki：国立長寿医療研究センター
受付日：2011.12.6．採用日：2012.3.15

転倒恐怖感と関連する因子として明らかとなっている．さらに，縦断的な研究では，転倒恐怖感を有する地域在住高齢者は，将来，日常生活活動（Activity of daily living，以下ADLと略す）障害を引き起こしやすい[11]という報告もされておりその重要性は明確である．

これまでの研究では，転倒恐怖感によりADLに影響のある高齢者についての報告が多くなされているが，一方で，転倒恐怖感はあるが日常生活に支障はないと回答する対象者も多く存在すると報告されている[12]．しかし，ADLの保たれた高齢者にどの程度，転倒恐怖感が存在し，それが，どのような因子と関連しているかは明らかではない．

本研究では，手段的日常生活活動（Instrumental activity of daily living，以下IADLと略す）が自立した地域在住高齢者の転倒恐怖感の存在率，及びその関連要因を検討することを目的とした．

方　法

対象者は，国立長寿医療研究センターが保有する65歳以上の地域在住高齢者を対象としたデータベース（n＝1,543）から，重度の脳卒中，心疾患の既往のある者と明らかに調査が遂行できないと判断された者を除外した．さらに，調査協力が得られ全ての検査が実施できた者から，IADLが自立していない高齢者を除外し，119名（平均年齢75.7±7.2歳，男性59名，女性60名）を本研究の対象とした．なおIADLの評価は老研式活動能力指標を用い，手段的自立の項目である「バスや電車を使って1人で外出できますか」「日用品の買い物ができますか」「自分で食事の用意ができますか」「請求書の支払いができますか」「銀行貯金・郵便貯金の出し入れが自分でできますか」に全て「はい」と回答した者をIADL自立とした．対象者には本研究の主旨および目的を口頭と書面にて説明し，書面にて同意を得た．なお，本研究は国立長寿医療研究センター倫理・利益相反審査委員会の承認を受けて実施した．

転倒恐怖感の聴取は，「現在，転ぶことに対してどのような怖さを持っていますか」と質問し，「全く怖くない」「怖くない」「やや怖い」「大変怖い」の4つの選択肢から回答を求め，「全く怖くない」「怖くない」と回答した者を転倒恐怖感なし群とし，「やや怖い」「大変怖い」と回答した者を転倒恐怖感あり群とした．さらに，転倒恐怖感が日常生活に影響を及ぼすかどうかを聴取した．

調査項目は，これまで転倒恐怖感に関連すると報告されている基本属性，健康状態，転倒歴，運動機能，心理状態に加えより高次の能力を評価するため身体活動量と生活空間の指標も含めた．基本属性として年齢，性別を聴取し，身長と体重を測定しBody Mass Index（以下BMIと略す）を算出した．健康状態については，慢性疾患の既往歴，服薬，痛みを聴取した．慢性疾患の既往歴において，高血圧，糖尿病，心疾患，脳血管疾患のいずれかの既往がある場合を「慢性疾患の既往歴あり」とした．先行研究で転倒の予測因子として報告されている服薬数に着目し[13]，現在飲んでいる薬を種類ごとに尋ね，合計3種類以上の服薬がある場合を「3種類以上の服用あり」とした．痛みは，健康関連QOLの一側面として捉えている先行研究に着目し[14]，SF-8の痛みに関する下位項目を用い，「過去1カ月間に身体の痛みはどのくらいありましたか」という質問に対し，「ぜんぜんなかった」「かすかな痛み」「軽い痛み」「中くらいの痛み」「強い痛み」「非常に強い痛み」の中から回答を求めた．「ぜんぜんなかった」を選択した者を「痛みなし」とし，その他5項目を選択した者を「痛みあり」とした．転倒歴は過去1年間の転倒回数を尋ね，1回以上転倒している者を「転倒経験あり」とした．転倒はGibson MJの定義[15]に基づき，「滑ったり，転んだり，つまずいたりなどしてバランスを崩し，足以外の体の一部が地面に触れたこと」とし，あらかじめ対象者に説明した．

身体機能検査としてTimed Up and Go test（以下TUGと略す），開眼片足立ち保持時間を測定した．TUGは椅座位から起立し3mを往復歩行した後に椅子へ着座するまでの所要時間をストップウォッチにて計測した．「普段歩いている速度」で2回計測を行い，所要時間の短い結果を採用した[16]．開眼片足立ち保持時間は，視線の高さに設定された視標点を注視しながら任意の脚を挙上し，片脚立位姿勢を保持するようにした．挙上脚が床面に接した時，あるいは立脚側が移動した時を終了とした．最大60秒までの時間を，ストップウォッチを用い2回測定し，保持時間の長い結果を採用した．心理状態はGeriatric Depression Scale（以下GDSと略す）を用いて調査した．GDSは15項目の質問に，「はい」か「いいえ」で答えるもので，得点は0～15点で得点が大きいほどうつ傾向が強いことを示す[17]．

身体活動量は，International Physical Activity Questionnaire（以下IPAQと略す）を用いた．IPAQは，1週間における高強度および中等度の身体活動を行う日数および時間を質問するものである．全9問から構成され，活動強度別に活動量を質問するshort versionを使用した[18]．生活空間の評価はLife-Space Assessment（以下LSAと略す）を用いた[19,20]．LSAは，各生活空間レベルに移動した頻度，移動における補助具（杖や車椅子）の

表1　各変数の全例及び転倒恐怖感の有無による比較

変数	全例（n＝119）	転倒恐怖感	
		あり（n＝61）	なし（n＝58）
年齢（歳）	75.7±7.2	76.6±6.8	74.8±7.0
性別（女性，%）	60（50.4）	40（65.6）	20（34.5）*
BMI（kg/m²）	23.1±3.3	22.9±3.6	23.2±3.0
慢性疾患の既往歴有り（人数，%）	54（45.4）	31（50.8）	23（39.7）*
3種類以上の服用有り（人数，%）	49（41.2）	29（47.5）	20（34.5）
痛み有り（人数，%）	76（63.9）	46（75.4）	30（51.7）*
転倒経験有り（人数，%）	40（33.6）	29（47.5）	11（19.0）*
TUG（秒）	9.1±2.3	9.6±2.4	8.5±2.0*
開眼片足立ち保持時間（秒）	33.3±23.8	28.8±22.8	40.0±23.5*
GDS（点）	3.6±3.2	4.0±3.4	3.4±2.9
IPAQ推定カロリー（kcal/日）	411.9±479.4	317.8±357.3	475.9±544.3
LSA（点）	95.5±17.6	88.2±18.6	101.1±15.2*

数値は平均値±標準偏差または人数（%）
対応のないt検定及びχ^2検定　*$p<0.05$
BMI＝Body Mass Index
TUG＝Timed Up and Go test
GDS＝Geriatric Depression Scale
IPAQ＝International Physical Activity Questionnaire
LSA＝Life-Space Assessment

必要性・介助者の必要性を調査する評価指標である．生活空間は，1）自宅内，2）自宅敷地内，3）自宅近隣，4）町内（概ね16 km以内），5）町外（概ね16 km以上）の5段階における移動の有無を聴取した．頻度は，週1回未満，週1～3回，週4～6回，毎日の4段階評価を各生活空間で聴取した．各生活空間得点（1～5点）に頻度（毎日：4点，4～6日：3点，1～3日：2点，1日未満：1点）と自立度の得点（自立：2点，物的介助あり：1.5点，人的介助あり：1点）を乗じて各生活空間の得点を算出した後，それら得点の和を算出してLSA得点とした．得点は0～120点となり，得点が大きいほどより生活空間が広く自立して活動できていることを意味している．以上の質問紙票はすべて日本語版を用いた．なお，調査項目はすべて事前にトレーニングを受けたスタッフが行った．

統計解析は，転倒恐怖感の有無によりわけられた2群間の比較を，連続変数に対しては対応のないt検定，カテゴリー変数にはχ^2検定を用いて検討した．これらの分析で有意な群間差を示した指標と転倒恐怖感の関連性を検討するために，多重ロジスティック回帰分析を行った．目的変数に転倒恐怖感の有無を，説明変数に有意な群間差を認めた項目に共変量として年齢，性別を加え，検討を行った．性別と「はい」と「いいえ」で表す名義尺度には女性と「はい」を1，男性と「いいえ」を0のダミー変数で表した．また，転倒恐怖感の有無でのLSAの下位項目を細かく検討するために，各生活空間レベルへの移動頻度，補助具の有無，介助者の有無と転倒恐怖感の有無にχ^2検定を行った．統計解析はSPSS for Windows 17.0を用い，有意水準は5%とした．

結　果

全対象者の特性及び転倒恐怖感の有無で分けた群ごとの特性を表1に示した．対象者のうち61名（51.3%）が転倒恐怖感を有していた．なお，転倒恐怖感を有する対象者は，全員，日常生活に影響はないと回答した．

基本属性では，年齢とBMIは群間において有意な差はなかったが，性別では，なし群（34.5%）に比べ，あり群（65.6%）に有意に女性が多かった（$p<0.05$）．健康状態では，「3種類以上の服用あり」では，有意な差はなかったが「過去1カ月に痛みあり」と「慢性疾患の既往歴あり」が転倒恐怖感あり群に有意に多く存在した（$p<0.05$）．

TUGでは，あり群（9.6±2.4秒）の方が，なし群（8.5±2.0秒）に比べ有意に遅く（$p<0.05$），開眼片足立ち保持時間では，あり群（28.8±22.8秒）が，なし群（40.0±23.5秒）に比べ有意に短かった（$p<0.05$）．LSAでは，あり群（88.2±18.6点）がなし群（101.1±15.2点）に比べ有意に低値を示した（$p<0.05$）．

単変量解析で有意な差を示した性別，「過去1年間の転倒経験」，「過去1カ月の痛み」，「慢性疾患の既往歴」，

表2　転倒恐怖感を従属変数とした多重ロジスティック回帰分析

独立変数	オッズ比	オッズ比の95%信頼区間	
		下限	上限
年齢（歳）	0.99	0.91	1.07
性別（女/男）	2.01	0.80	5.06
慢性疾患の既往歴（有/無）	0.69	0.26	1.83
痛み（有/無）	2.58	0.99	6.68
転倒経験（有/無）	0.60	0.22	1.66
TUG（秒）	1.06	0.79	1.40
開眼片足立ち保持時間（秒）	0.98	0.96	1.01
LSA（点）	0.96*	0.93	0.99

*p<0.05
TUG＝Timed Up and Go test
LSA＝Life-Space Assessment

表3　転倒恐怖感の有無におけるLSAの下位項目の分布

LSA下位項目		転倒恐怖感 あり（n＝61）	転倒恐怖感 なし（n＝58）
自宅近隣	頻度		
	毎日	57	58
	週4～6回	5	0
	補助具（あり）	1	0
	他者の助け（あり）	0	0
町内	頻度*		
	毎日	29	48
	週4～6回	12	7
	週1～3回	17	3
	週1回未満	3	0
	補助具（あり）*	6	0
	他者の助け（あり）	1	0
町外	頻度		
	毎日	8	14
	週4～6回	3	9
	週1～3回	25	23
	週1回未満	22	11
	なし	4	1
	補助具（あり）*	5	0
	介助者（あり）*	9	2

数値は人数
すべての対象者が補助具，介助者を必要とせず「自宅内」「自宅敷地内」に毎日移動しているため2項目を割愛
χ^2検定　*p<0.05

TUG，開眼片足立ち保持時間，LSAと年齢を独立変数として多重ロジスティック回帰分析の強制投入法を用いた結果を表2に示す．LSA（オッズ比：0.96，95%信頼区間：0.93～0.99　p＝0.004）が転倒恐怖感の有無と独立して関連性を示し，他の変数では有意な関連は示されなかった．

表3にLSAの下位項目の分布を転倒恐怖感の有無で，群ごとに示した．LSAの町内の項目では，転倒恐怖感あり群で，なし群に比べ，有意に移動頻度が少なく，補助具を必要とする者が多かった．町外の項目では，あり群で，なし群に比べ，有意に補助具，介助者を必要とする者が多かった．

考　察

本研究では，IADLが自立した65歳以上の地域在住高齢者119名を対象とし転倒恐怖感の存在率及びその関連する要因を検討した．その結果，転倒恐怖感は対象者の51.3%に存在し，その全員が転倒恐怖感は日常生活に支障はないと回答した．転倒恐怖感の有無による群間比較では性別，慢性疾患の既往歴の有無，痛みの有無，過去1年間の転倒経験の有無，TUG，開眼片足立ち保持時間，LSAが有意な差および関連を示し，それらと年齢を独立変数とした多重ロジスティック回帰分析では，LSAのみが転倒恐怖感の有無と有意な関連性を示した．

転倒恐怖感に関する先行研究では，転倒恐怖感の存在率は21%～85%と報告されているが，存在率が85%を示す研究[3]では，対象者の取り込みがプライマリーケアを受診した者であり，他の報告よりもより虚弱な高齢者が対象となったものと考えられる．その研究を除くと21%～60%である．一方，本研究では，IADLが自立している者に対象を絞ったにもかかわらず51.3%と地域在住高齢者全体を対象としたこれまでの報告と比べても同等の値であった．

これまでの報告では，日常生活に影響のある転倒恐怖感は，年齢や性別などの基本属性に加え過去の転倒経験[4,5]，健康状態[6,7]歩行，バランス[8]などの身体機能，さらに抑うつや不安[9,10]などの心理的状態と関連があり，また，転倒恐怖感を有する高齢者は，有さない者に比べ，将来の日常生活活動障害を引き起こしやすい[11]と報告されている．本研究の結果も過去の研究と一部合致し，さらに生活空間については新たな関連が示された．IADLが自立している高齢者の転倒恐怖感は，これまでの報告とは性質が異なるものと考えられる．さらにLSAの下位項目の分布から，自宅の近所よりも広い範囲，つまり町内や町外に移動する頻度や，その際に補助具，介助者が必要かどうかと転倒恐怖感が関連するということが示唆される．

生活空間の狭小化は，高齢者の生理的予備能の低下を

示す事象であり，虚弱発生の独立した予測因子であると報告されてきた[20]．そのため，健康増進や身心機能，ADL障害予防のために生活空間の拡大が注目されている．地域在住高齢者を対象とした我々のこれまでの報告では，自宅の外に出る頻度が1週間に1回以下である者はADL障害を生じやすく，自宅の近所まで出かける頻度が1週間に1回以下である者はIADL障害を生じやすいことが明らかになった[21]．また，地域在住高齢者の1年後のIADL障害はTUGとLSAの得点の組み合わせで予測できるという結果も示した[22]．このように生活空間の範囲は，将来のADL，IADL障害と密接な関係があり，生活空間の維持，拡大を目的とした介入の重要性が挙げられる．

なお，本研究での転倒恐怖感の聴取は，転倒恐怖感の有無を指標としており，過去の報告で指摘があるように[23]，転倒恐怖感が発生する機転やどういった場面で転倒恐怖感が生じているかなどの質的な情報は把握していない．今後，IADLが自立している高齢者に転倒恐怖感が生じた機転や普段どういった活動で転倒恐怖感を持つかなどの詳細な情報を聴取し，その構造を明らかにすることで，よりよい介入方法の立案に結びつくと考えられる．また，本研究で扱った指標は，転倒恐怖感に関連する社会的支援の有無や対象者の住宅環境，住宅周囲の状態などの外的要因[24,25]を含んでおらずこれらの指標の影響については考慮できていない．

本研究では，IADLの保たれた高齢者の転倒恐怖感と生活空間の横断的な関係は明らかとなった．今後，縦断的な調査によって，この因果関係や関連の構造を明らかにし，ADL，IADL障害予防のための適切な介入方法の確立が望まれる．

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Factors associated with fear of falling among community-dwelling elderly adults without reduced performance in instrumental activities of daily living

Toshihisa Oya[1], Yasushi Uchiyama[1], Hiroyuki Shimada[2], Hyuma Makizako[2,3], Takehiko Doi[2], Daisuke Yoshida[2,4], Kazuki Uemura[1,3] and Takao Suzuki[5]

Abstract

Aim: The purpose of this study was to examine factors related to fear of falling (FOF) in elderly adults who showed no reduced performance regarding independent instrumental activities of daily living (IADL).

Methods: A total of 119 elderly adults participated in the study (mean age, 75.7±7.2 years, women, n=60). We investigated the prevalence of FOF, anamnesis, medications, body pain, and history of falls, the Geriatric Depression Scale, International Physical Activity Questionnaire, Life-Space Assessment (LSA). The Timed Up and Go test (TUG) and one-legged standing time were measured to evaluate physical performance. Participants were divided into elderly adults with FOF (FOF group) and those without FOF (non-FOF group). The unpaired t-test or chi-square test was used for group comparisons. Multiple logistic regression analysis was then performed to examine the factors associated with FOF.

Results: The prevalence of FOF was 51.3% overall. The FOF group had a higher prevalence of anamnesis, body pain, and history of falls than the non-FOF group. The FOF group had lower LSA scores, longer durations on the TUG, and shorter durations on the one-legged standing test than the non-FOF group. On multiple logistic regression analysis, LSA (total score, 120 points) was significantly associated with FOF (odds ratio: 0.96, 95% confidence interval = 0.93-0.99).

Conclusion: Fear of falling was significantly associated with life space in community-dwelling elderly adults who showed no reduced performance regarding IADL. In future, it will be necessary to clarify any possible causal relationship by longitudinal investigations.

Key words: *Community-dwelling elderly, Fear of falling, Life space*
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1) Department of Physical Therapy Program in Physical and Occupational Therapy, Nagoya University Graduate School of Health Science
2) Section for Health Promotion, Department of Health and Medical Care, Center for Development of Advanced Medicine for Dementia, National Center for Geriatrics and Gerontology
3) Research Fellow of the Japan Society for the Promotion of Science
4) Japan Foundation for Aging and Health
5) National Institute for Longevity Sciences, National Center for Geriatrics and Gerontology

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■原 著

ステップエルゴメーターのアイソキネティック運動におけるピークパワーと筋活動特性との関連

—表面筋電図周波数分析による検討—

The Relationship between Peak Power of Isokinetic Exercise on a Step Ergometer and Muscle Activity Characteristics —Surface EMG Frequency Analysis—

水本 淳[1)] 島田 裕之[2)] 井平 光[1)]
野村 知広[1)] 古名 丈人[1)] 鈴川 芽久美[3)]

ATSUSHI MIZUMOTO[1)], HIROYUKI SHIMADA[2)], HIKARU IIHIRA[1)],
TOMOHIRO NOMURA[1)], TAKETO FURUNA[1)], MEGUMI SUZUKAWA[3)]

[1)] *Graduate School of Health Sciences, Sapporo Medical University: –South 1 West 17, Chuoh-ku, Sapporo, Hokkaido, 060-8556, Japan. TEL+81 11-611-2111 E-mail: a.mizumoto@sapmed.ac.jp*
[2)] *Section for Health Promotion, Department of Health and Medical Care, Center for Development of Advanced Medicine for Dementia, National Center for Geriatrics and Gerontology*
[3)] *Department of Rehabilitation, Faculty of Health Sciences, University of Human Arts and Science*

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ABSTRACT: [Purpose] The aim of this study was to examine the relationship between peak power of the lower extremities during isokinetic movement on a step ergometer and muscle activity characteristics using EMG frequency analysis of community-dwelling elderly adults. [Methods] Twelve elderly women (mean age 78.3 years) were measured for muscle power on a step ergometer (60 and 90 steps / minute), and surface electromyograms (EMG) of the lower extremities. EMG data was wavelet transformed and MPF (Mean Power Frequency), LF / TP (Low Frequency per Total Power) and HF / TP (High Frequency per Total Power) were calculated. [Results] The muscle power at 60 steps / min showed a significant correlation with the LF / TP of the tibialis anterior. MPF of the vastus medialis and tibialis anterior at 90 steps / min were higher than at 60 steps /min. [Conclusion] We speculate that fast-twitch muscles activity at 90 steps / min increases, therefore we consider that high speed movement is useful for preventing the sarcopenia.

Key words: muscle power, wavelet transform, Biostep

要旨：〔目的〕Biostep のアイソキネティック運動時の筋パワーと筋活動特性との関連を調べ，速度条件による活動特性の違いを検討した．〔対象と方法〕高齢女性 12 名に対し 60 steps / min と 90 steps / min 駆動時の筋パワーと表面筋電図を測定した．筋電図はウェーブレット変換を行った後，MPF，LF/TP，HF/TP を算出した．各変数の相関分析と，条件比較のため wilcoxon 検定を行った．〔結果〕60 step の筋パワーと前脛骨筋の LF/TP の間に有意な正の相関を認めた．内側広筋，前脛骨筋の MPF，HF/TP が 90 step で有意に高かった．〔結語〕90 step の運動において速筋線維の活動が増加することが推察され，加齢による速筋線維の萎縮に対して高速運動が有効であると考えられた．

キーワード：筋パワー（筋仕事率），ウェーブレット変換，Biostep

[1)] 札幌医科大学大学院 保健医療学研究科：北海道札幌市中央区南 1 条西 17 丁目（〒 060-8556）TEL 011-611-2111
[2)] 国立長寿医療研究センター 認知症先進医療開発センター 在宅医療・自立支援開発部 自立支援システム開発室
[3)] 人間総合科学大学 保健医療学部 リハビリテーション学科

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I. はじめに

加齢に伴う筋量の減少や筋力の低下はサルコペニアと呼ばれ，サルコペニアの臨床定義や診断基準を提案したEuropean Working Group on Sarcopenia in Older Peopleの報告では，サルコペニアを筋量の低下と筋機能（筋力やパフォーマンス）の低下により定義しており[1]，高齢期における筋機能の重要性が改めて注目されている．高齢者において筋力低下は日常生活活動（activity of daily living: ADL）能力の低下を引き起こす要因である．特に下肢の筋力低下は，立ち上がりや歩行，階段昇降など起居，移動を中心としたADL動作制限の原因となる[2,3]．加齢に伴う筋萎縮は，遅筋線維に比べ速筋線維の萎縮が著しく，特にtype IIa線維が選択的に萎縮することが報告されている[4,5]．また，加齢によって筋量の減少や筋線維の萎縮のみならず，等尺性運動時の筋力および等速性（アイソキネティック）運動時の筋パワーの低下が生じることが明らかにされている[6]．筋力は力の発揮能力であり，筋パワーは瞬間的に筋力を発揮する能力（力×速さ）と定義されている[7]．加齢により最大筋力だけではなく筋パワーも著明に低下し，とりわけ速筋線維に関連した高速度でのアイソキネティック運動時の筋パワーの低下が著しいといわれている[8,9]．筋パワーの低下は，筋力と比較してADL動作の遂行に重要であることが指摘されており[10,11]，加齢によるADL能力低下を予測して予防するためには，等速性運動機器による筋パワーの測定が重要であると考えられる．

以前，我々は地域高齢者の筋パワーを測定する手段として，ステップエルゴメーターを用いたアイソキネティック運動時の筋パワー評価法を提案した[12]．その結果，アイソキネティックモード90 steps/minにおけるピークパワーが，最大努力下でのtimed up and go test（TUG）の時間との間に高い相関を認め，筋パワー評価法としての基準関連妥当性が示された．また，60 steps/ minよりも90 steps/minのような高速度の運動の方が，TUGのような運動を速く遂行することが求められる課題に強く関係することが予想された．しかし，ステップエルゴメーター駆動のピークパワーに至る過程における，各筋の活動の違いは明らかではなく，速度の違いによる筋活動の変化についても不明であった．筋活動の評価指標である表面筋電図は，筋積分値の評価により運動単位の動員様式，インパルス発射頻度を反映した総合的な評価が可能であるが，動員された筋線維タイプの種類を推測することは困難である．筋電図周波数解析は，筋の質的評価として用いられており，周波数解析によって得られたパワースペクトルは筋活動に参加している運動単位の数や種類[13]，インパルス発射頻度[14]，同期化[15]および筋線維伝導速度[16]などを反映しているといわれており，定常信号波形の解析には時間領域から周波数領域へと変換する手法であるフーリエ変換が用いられている．一方，時間的に周波数が変動する非定常信号波形の解析には，フーリエ変換は用いることができず，アナライジングウェーブレットに対する伸縮・拡張，平行移動の操作の組み合わせにより，周波数と時間を同時に処理できるウェーブレット変換（wavelet transform）を用いることで，動的な収縮における周波数解析を行うことが可能となる[17,18]．

本研究では，ステップエルゴメーターを用いて高齢者のアイソキネティック運動時の下肢筋電図波形の周波数解析により，下肢筋パワーと各筋の活動特性との関連を明らかにすることを目的とした．また，駆動速度の違いによる筋の活動特性の違いを併せて検討した．速度の違いによる筋の活動特性を示すことで，ステップエルゴメーターを用いた運動処方や，筋パワーの評価を行う上で有益な知見を得ることができると考えられた．

II. 対象と方法

1. 対象

東京都板橋区に在住する下肢疾患の既往のない，歩行および手段的ADLが自立している地域在住高齢者女性12名（平均年齢78.3 ± 2.6歳，平均身長145.6 ± 3.3，平均体重51.3 ± 4.9）を対象とした（表1）．対象者には本研究の主旨と目的，方法を口頭，書面にて十分に説明し，本人の同意を得た．なお本研究は，東京都健康長寿医療センターの倫理審査委員会で承認されたものである．

2. 方法

筋パワーの測定はアイソキネティック運動が可能な運動機器であるステップエルゴメーター（BIODEX Biostep，酒井医療株式会社，日本）を用いて実施し，目標ステップ数はアイソキネティックモードの60 steps / min（60 step），90 steps / min（90 step）と設定した．駆動時間を15秒間に設定し，シート位置はステップエルゴメーター駆動時の最大伸展時での膝関節屈曲角度が20度になるように調節し，上肢はシート横のハンドグリップを把持させた．本研究で施行させた運動はアイソキネティック運動であり，設定したステップ数に達するとパワーに応じた負荷がかかるため，測定前に目標ステップ数に達するように十分な練習を行った．ステップエルゴメーターの駆動開始時には重く感じることもあるが，それに負け

表1 対象者の基本属性

(N = 12)

年齢		(歳)	78.3 ± 2.6
BMI		(kg/m^2)	24.2 ± 2.1
ピークパワー	60 step	(W)	327.1 ± 42.8
	90 step	(W)	259.6 ± 84.0

※平均 ± 標準偏差

ないように速く漕ぐようにと説明した．測定開始時には「全力で漕いで，それを15秒間保つように」と教示し，測定中は目標ステップ数が維持できるように「そのまま維持するように」と声掛けを行った．測定回数はそれぞれ1回とし，施行間は3分以上の休憩を挟み，口頭にて疲労感がないことを確認した．60 step，90 stepの施行順はコイントスにてランダムに設定した．駆動時のパワー（仕事率；W）は，解析ソフト（SpErgo2，酒井医療株式会社，日本）を用い，駆動開始からサンプリング周波数1Hzにて測定した．目標ステップ数に達した後の最大値をピークパワーとした．

駆動時の筋活動は，表面筋電図測定装置（Noraxon MyoTrace400，酒井医療株式会社，日本）を用い，サンプリング周波数を1000Hzとし，パワーの測定開始と筋電図測定を手動にて同期させて測定を行った．筋電位の信号をA/D変換し，パーソナルコンピュータに取り込んだ後，専用ソフト（Noraxon MyoResearch XP，酒井医療株式会社，日本）を用い，データの抽出を行った．被検筋は右下肢の内側広筋（VM），半腱様筋（ST），前脛骨筋（TA），腓腹筋内側頭（MG）の4筋とした．皮膚前処置剤およびアルコール綿にて処置を行った後，電極中心距離を2 cmとし，電極Bluc sensor(ambu社，デンマーク）を筋線維の走行に沿って貼り付けた．電極貼り付け位置は，内側広筋は膝蓋骨上端から内側2～3横指の位置，半腱様筋は坐骨結節と脛骨内側顆を結ぶ線の遠位3分の1の位置，前脛骨筋は腓骨頭より内下側3～4横指の位置，腓腹筋内側は脛骨内側顆と踵骨を結ぶ線の近位3分の1の位置，アース電極は大腿骨外側上顆とした[19]．駆動時の筋収縮は，安静時の基線の平均＋2標準偏差を超えた時点を筋収縮とした．SpErgo2によるパワーおよびステップ数のグラフから，ピークパワーにおける時間を得た後，その時間を含む6駆動分の筋収縮を選択した．各々ピークパワーを発揮する時間は異なっており，ピークパワーから駆動終了までの間で，波形が安定している連続した駆動における筋の活動特性を比較するため，6駆動分を解析区間とした．すなわち60 step（1stepあたり1秒）の場合は6秒間，90 step（1stepあたり0.67秒）の場合は4秒間を解析区間とした．

6駆動分のデータは数値解析ソフトウェアScilab Ver.5.3.1（INRIA，フランス）を使用し，wavelet toolboxのプログラムを利用しmorlet関数を用いた連続ウェーブレット変換によるパワースペクトル解析を行った．解析周波数帯域は先行研究[20]に準拠し，11～200Hzとし，時間成分ごとのパワーを平均化した後，6駆動分のパワーの総和（Total power：以下TP）および45Hz以下の低周波帯域のパワーの合計（Low Frequency：LF），75Hz以上を高周波数帯域（High Frequency：HF）としたパワーの合計を算出した．そこからTPに対する低周波帯域の割合（LF/TP），高周波帯域の割合（HF/TP），および下記の式を用いて平均パワー周波数（Mean Power Frequency：MPF）を算出し，それぞれ分析対象とした．

$$MPF=\int_0^\infty fP(f)\,df \Big/ \int_0^\infty P(f)\,df \qquad P：\text{power値}，f：\text{周波数}$$

統計学的解析には，各変数に対しShapiro-Wilk検定を行い，正規性を確認できない変数が含まれていたため，ノンパラメトリック検定を使用した．各step数におけるピークパワーと各筋の活動特性との関係を調べるため，Spearmanの順位相関係数を算出した．また，60 stepと90 stepの駆動における筋の活動特性を比較するため，Wilcoxonの符号付順位和検定を行った．統計学的有意水準は5%とし，統計解析ソフト（IBM SPSS Statistics 19，日本IBM，日本）を用いた．

III. 結　果

60 step時のピークパワーの平均値は327.1 ± 42.8Wであり，90 step時のピークパワーの平均値は259.6 ± 84.0Wであった（表1）．60 step時のピークパワーと相関関係にあった変数は，前脛骨筋のMPF（$\rho = -.769$，$p < 0.01$），HF/TP（$\rho = .580$，$p < 0.05$）および前脛骨筋のLF/TP（$\rho = -.615$，$p < 0.05$）であった（表2）．一方で，90 step時のピークパワーは，有意な相関が認められなかった．MPFは，内側広筋，前脛骨筋ともに60 step時よりも90 step時の方が有意に高かった（それぞれ$Z = -2.510$，$p < 0.05$，$Z = -3.059$，$p < 0.01$），LF/TPは，内側広筋，前脛骨筋ともに60 step時よりも90 step時の方が有意に低かった（それぞれ$Z = -2.353$，$p < 0.05$，$Z = -2.667$，$p < 0.01$），HF/TPは，内側広筋，前脛骨筋ともに60 step

表2　ピークパワーと筋の活動特性との相関係数

	年齢	BMI	内側広筋			半腱様筋			前脛骨筋			腓腹筋（内側）		
			MPF	LF/TP	HF/TP	MPF	LF/TP	HF/TP	MPF	LF/TP	HF/TP	MPF	LF/TP	HF/TP
60 step時のピークパワー	.029	−.161	.070	−.098	.154	.035	−.336	.140	−.769**	.580*	−.615*	.007	.091	−.021
90 step時のピークパワー	−.298	−.378	.147	−.273	.364	−.336	.140	−.301	−.329	.371	−.462	.084	.140	−.098

※spearman'sρ，*：$p<0.05$，**：$p<0.01$

表3 60 stepと90 stepの駆動における筋の活動特性の差

		内側広筋			半腱様筋		前脛骨筋			腓腹筋(内側)	
		60 step	90 step		60 step	90 step	60 step	90 step		60 step	90 step
MPF	(Hz)	84.5 ± 12.2	92.4 ± 13.5	*	104.3 ± 15.9	103.7 ± 13.4	84.7 ± 6.7	95.3 ± 10.5	**	107.6 ± 10.4	112.7 ± 13.4
LF/TP	(%)	36.3 ± 9.0	31.3 ± 8.4	*	20.4 ± 9.1	19.2 ± 7.8	31.8 ± 5.0	26.4 ± 6.4	**	15.7 ± 5.5	13.7 ± 5.2
HF/TP	(%)	49.1 ± 10.2	54.6 ± 9.5	*	65.2 ± 12.9	66.5 ± 10.6	49.4 ± 6.1	57.7 ± 8.6	**	70.2 ± 7.5	73.0 ± 9.3

※*: $p<0.05$, **: $p<0.01$

時よりも90 step時の方が有意に高かった（それぞれ$Z=-2.197$, $p<0.05$, $Z=-2.981$, $p<0.01$）(表3).

IV. 考 察

これまでステップエルゴメーター駆動は，サイクルエルゴメーターと比較し，大腿四頭筋の筋活動が高いことが知られている[21]ものの，ピークパワーまでの過程で，どの筋がどの程度活動しているかという部分は明らかにされていなかった．筋活動に参加している筋線維タイプとパワースペクトルの関係では，40Hz以下の低周波域はtype I線維，46～80Hzの中周波数帯域はtype IIa線維，81Hz以上の高周波数帯域ではtype IIb線維の活動に対応し[13]，低周波数帯域は遅筋系，高周波数帯は速筋系の活動を反映しているといわれている[22]．MPFは筋疲労の指標として用いられることが多く，疲労によりMPF低下が生じることが明らかにされている[20]．今回は，短時間の駆動での解析であり，筋疲労ではなく駆動条件による筋の活動特性の違いを検討するために，MPFを解析値として使用した．また，活動における低周波数成分と高周波数成分の相対的な割合を比較するために，LF/TPとHF/TPを解析値として使用した．

本研究の結果より，60 step時のピークパワーでは，前脛骨筋のMPF，およびHF/TPとの間にそれぞれ有意な負の相関が認められ，LF/TPとの間には有意な正の相関が認められた．60 step駆動時の前脛骨筋による低周波数帯域の筋活動の高さと，高周波数帯域の筋活動の低さ，すなわちMPFの低さとピークパワーの高さが関連していることから，強い力を発揮するよりも遅筋線維を中心とする駆動時の持続的な足関節固定のための筋活動が高まり，安定したステップ運動が可能になることにより高いパワーを発揮することに繋がったと推察された．また，多機能エルゴメーター（ストレングスエルゴ）の研究では，駆動速度が高まると屈曲相の前脛骨筋の活動が高まり，下肢引き上げの補助的作用や足関節背屈位による駆動を円滑にする作用が生じると述べられており[23]，ステップエルゴメーター駆動においても前脛骨筋に関しては多くの対象者で類似の作用が生じていた可能性があった．60 step，90 step時の内側広筋，半腱様筋，腓腹筋，90 step時の前脛骨筋ではピークパワーと筋の活動特性との間に有意な相関は認められなかった．このことは，ステップエルゴメーターを全力で駆動する戦略が個人により異なっていることが考えられた．測定前に十分な駆動練習を行っているものの，主要な移動手段である自転車（エルゴメーター）駆動に比較すると慣れない運動であり，アイソキネティック運動の強い抵抗を受け，それを下肢で押し出す（蹴り出す）動きの際に，体幹筋，股関節周囲筋，および膝関節周囲筋などの筋の活動戦略は個人間でばらつきが大きいことが考えられた．また，90 stepの前脛骨筋は，60 stepと同様に屈曲相の足の引き上げや足部の固定機能に関与すること予測されたものの，速度の増加に対応した前脛骨筋の活動が十分に発揮できなかった可能性が考えられた．本研究のデザインでは，駆動相ごとの分析は困難であるため，今後は駆動相ごとの筋活動の変化を検討していく必要があるといえる．

また，60 stepと90 stepにおける，筋の活動特性の比較では，内側広筋および前脛骨筋では60 stepよりも90 stepでMPF，HF/TPの有意な増加，LF/TPの有意な低下が認められた．この結果から，より速い速度での運動において，高周波数帯域の筋活動，つまり速筋線維の筋活動の増加やインパルスの発射頻度の増加が起こることが推察された．多機能エルゴメーター駆動において，半腱様筋や腓腹筋は速度の増加により，伸展相での筋活動が増加することが示されている[23]が，ステップエルゴメーター駆動においては速度変化に対しても速筋線維の活動やインパルスの発射頻度が変化しない可能性が考えられた．

本研究の結果では，ステップエルゴメーター駆動時のピークパワーと筋の活動特性との関連は60 step時の前脛骨筋以外に認められず，ピークパワーの評価のみで筋の活動特性の把握は困難であるといえた．近年では，加齢による筋量の減少だけでなく，α運動ニューロン活動の低下や，運動に動員される運動単位の減少など神経機構の変化を，ダイナペニア(dynapenia)と表している[24]．また，生理学的な研究では，筋小胞体からのCa^{2+}放出量の低下による興奮収縮連関における情報伝達効率の低下や，筋原線維の張力産生能力の低下などが加齢で生じることが明らかになりつつある[25]．そのため，高齢者に対し筋の収縮速度や筋パワーの評価が重要視されている．本研究の結果から，筋パワーの評価に加え，筋の活動特性

の評価を行い，継時的な変化を追うことは，加齢で変化しうる速筋線維の割合やインパルスの発射頻度，神経伝導速度などが複合した要因の変化を追うことができるため，ダイナペニアの評価に有益であると考えられる．また，60 stepよりも90 stepの方がより高周波数帯域の割合が高かったことから，臨床的に，ステップエルゴメーターを用いる場合は，より速い運動課題を与えることで，Type IIb線維のような速筋線維の活動が賦活できると考えられ，サルコペニアやダイナペニアの予防に有益であると考えられた．本研究は横断調査であり，因果関係までは述べられないことや，Biostep解析ソフトのサンプリング周波数の制限から，駆動における相ごとの解析が困難である点が限界点として挙げられた．

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Gait adaptability and brain activity during unaccustomed treadmill walking in healthy elderly females

Hiroyuki Shimada [a,*], Kenji Ishii [b], Kiichi Ishiwata [b], Keiichi Oda [b], Megumi Suzukawa [c], Hyuma Makizako [a], Takehiko Doi [a], Takao Suzuki [d]

[a] Section for Health Promotion, Department for Research and Development to Support Independent Life of Elderly, Center for Gerontology and Social Science, National Center for Geriatrics and Gerontology, Japan
[b] Research Team for Neuroimaging, Tokyo Metropolitan Institute of Gerontology, Japan
[c] Faculty of Health Science, Department of Rehabilitation, Course of Physical Therapy, University of Human Arts and Science, Japan
[d] Research Center, National Center for Geriatrics and Gerontology, Japan

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ABSTRACT

This study evaluated brain activity during unaccustomed treadmill walking using positron emission tomography (PET) and [^{18}F]fluorodeoxyglucose. Twenty-four healthy elderly females (75–82 years) participated in this study. Two PET scans were performed after 25 min of rest and after walking for 25 min at 2.0 km/h on a treadmill. Participants were divided into low and high step-length variability groups according to the median coefficient of variation in step length during treadmill walking. We compared the regional changes in brain glucose metabolism between the two groups. The most prominent relative activations during treadmill walking compared to rest in both groups were found in the primary sensorimotor areas, occipital lobe, and anterior and posterior lobe of the cerebellum. The high step-length variability group showed significant relative deactivations in the frontal lobe and the inferior temporal gyrus during treadmill walking. There was a significant relative activation of the primary sensorimotor area in the low step-length variability group compared to the high step-length variability group ($P = 0.022$). Compared to the low step-length variability group, the high step-length variability group exhibited a greater relative deactivation in the white matter of the middle and superior temporal gyrus ($P = 0.032$) and hippocampus ($P = 0.034$) during treadmill walking compared to resting. These results suggest that activation of the primary sensorimotor area, prefrontal area, and temporal lobe, especially the hippocampus, is associated with gait adaptability during unaccustomed treadmill walking.

1. Introduction

Increased gait instability and inconsistency from one step to the next are common in many elderly adults [1,2]. Gait variability, such as the coefficient of variation (CV) in step length [1,2], is a quantifiable feature of walking that is altered in clinical situations, such as falling, frailty, and gait disorders in neurodegenerative diseases [3–5]. The increase in gait instability observed in elderly adults without apparent neurological disease is multifactorial. Age-associated changes may contribute to gait instability, including reduced range of motion, decreased aerobic capacity and muscle function, and impaired balance [6,7]. However, the relationship between gait instability and brain function has not been studied in detail.

Gait is a complex sensorimotor action that is based on automated and reflexive spinal programs that are under the control of several distinct supraspinal centers located in the brainstem, basal ganglia, cerebellum, and cerebral cortex. Several imaging techniques have been developed to identify activation patterns during walking. These include the measurement of glucose metabolism during actual walking using positron emission tomography (PET) with [^{18}F]fluorodeoxyglucose (FDG) [8–10] and single-photon emission tomography (SPECT) with technetium-99m hexamethylpropylene amine oxime or ^{99m}Tc-ethyl cysteinate dimer to measure fixed regional cerebral blood flow [11–13].

Previous PET and SPECT studies revealed that gait disturbance in Parkinson's disease may be associated with underactivity in the medial motor area and cerebellar hemispheres and overactivity in the cerebellar vermis [8,10–12] Recently, it was reported that elderly adults with gait disturbance, secondary to age-related white matter changes, exhibited underactivation

* Corresponding author at: Section for Health Promotion, Department of Health and Medical Care, Center for Development of Advanced Medicine for Dementia, National Center for Geriatrics and Gerontology, 35 Gengo, Morioka-machi, Obu, Aichi 474-8511, Japan. Tel.: +81 562 44 5651x5254; fax: +81 562 46 8294.
E-mail address: shimada@ncgg.go.jp (H. Shimada).

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of the supplementary motor area, thalamus, and basal ganglia compared to elderly adults without gait disturbance [13].

Treadmills are commonly used for gait analysis in clinical and research settings [14]. Treadmill walking, in theory, is mechanically equivalent to overground walking [15,16]. In reality, however, walking on a treadmill can initially be an unfamiliar experience [16,17]. Unimpaired younger adults required 4–6 min to familiarize themselves with the treadmill [14,17]. However, complete familiarization with treadmill in a 15-min single session was not attained in elderly adults [18]. Therefore, a treadmill walking task may be used to investigate the process of adaptation to an unfamiliar environment during walking.

The purpose of the study was, first, to compare the relative brain activation and/or deactivation during treadmill walking compared to resting condition and, second, to determine whether gait adaptability measured as gait variability could be explained through differences of brain activation and/or deactivation in response to an unaccustomed treadmill walk in the elderly adults.

2. Materials and methods

Two hundred and seventy-four females were selected from our database of elderly volunteers ($n = 1289$). Inclusion criteria were: age $\geq$ 75 years, no history of neurological or psychiatric disorders, cardiovascular disease, hypertension, heart failure, diabetes mellitus, head trauma, drug or alcohol abuse, or severe pain. Of the initial 274 females, 106 completed cognitive and physical performance tests including preferred walking speed. Sixty-nine females were excluded because of low cognitive function (Mini Mental State Examination score < 27 points), multiple medications, drug allergy, and gait disturbance (gait freezing, wide-based gait, or remarkable body sway during gait). Magnetic resonance imaging (MRI) with T1-weighted contrast was performed in 37 females using a 1.5-T Sigma Horizon scanner (GE, Milwaukee, WI, USA). Thirteen females were excluded based on MRI exclusion criteria (cerebrovascular lesions or high cortical atrophy). The remaining 24 females participated in the study (mean age, 78.0 ± 2.3 years; range, 75–82 years).

Participants were fully informed of the purpose and potential risks of the experiments, including radiation dose, and provided written, informed consent. The Ethics Committee of the Tokyo Metropolitan Institute of Gerontology approved the study protocol.

Brain glucose uptake in the rest and treadmill walking conditions was assessed on separate days (within two weeks, at least two days apart). Each condition consisted of three phases: preparation, rest or treadmill walking, and a PET scan. Total time of the FDG–PET measurement was about 85 min in each condition. The preparation period was 40 min in duration, after which the participants either rested for 35 min or walked for 25 min on a treadmill. A 6 min FDG–PET scan was performed subsequently.

During the preparation period, a catheter for injection of FDG was inserted into a vein of the left forearm. FDG (180 MBq) was injected intravenously at the onset of rest and treadmill walking. For the resting condition, participants lay supine with their eyes closed for 35 min. For the treadmill walking condition, participants walked on a treadmill (PW-21; Hitachi, Tokyo, Japan) for 25 min at 2.0 km/h while holding the handrails, to avoid falling during walking and to provide a uniform visual environment. The participants then rested on a bed with their eyes closed for 10 min.

A step counter with an infrared ray device (m-Stride ST-1100; S & ME, Tokyo, Japan) recorded walking speed, cadence, and step length during the treadmill walking period to evaluate temporal changes in gait characteristics. The step counter was placed on side-rail of a treadmill to measure belt speed (cm/s) of the treadmill and step time (s) during treadmill walking using infrared ray. The step length (cm) and cadence (steps/min) were calculated as follows.

$$\text{Step length} = \text{Belt speed} \times \text{Step time}, \quad (1)$$

$$\text{Cadence} = 60/\text{Step time}, \quad (2)$$

Step length was measured for 1 min at 0, 5, 10, 15, 20, and the 24th–25th min. We used 200 steps for the analysis of step length and cadence, 50 steps from each 1 min period starting at the 10th–11th min, 15th–16th min, 20th–21st min, 24th–25th min of treadmill walking. Five minutes following the rest or walking periods, PET scans were performed using a Headtome-V (SET 2400W, Shimadzu, Kyoto, Japan) in the three-dimensional (3D) mode. This 6 min emission scan therefore occurred 40 min after the intravenous injection of FDG. The scan produced images that had the following parameters: matrix size, 96 × 96 × 50; and voxel size, 2 mm × 2 mm × 3.125 mm. The attenuation was corrected via a transmission scan using a ^{68}Ga/^{68}Ge source.

The images were reconstructed using a filtered back projection algorithm with a second-order low-pass filter with a cutoff frequency of 1.25 cycles/cm. Corrections were applied for dead time and detector non-uniformity. Image processing and data analysis were performed using statistical parametric mapping (SPM8 software, Wellcome Department of Cognitive Neurology, Institute of Neurology, Queen Square, London, UK) implemented on MATLAB (MathWorks, Natick, MA, USA). The tasks performed using SPM8 were MRI/PET coregistration, spatial normalization, spatial smoothing, MRI segmentation, normalization, and SPM analysis. Anatomical brain MR images were spatially normalized into the Montreal Neurological Institute (MNI, McGill University, Montreal, Canada) standard template using an affine transformation (12 parameters for rigid transformations) [19]. The parameters were applied to the coregistered FDG–PET images. Therefore, all stereotactic coordinates given in this paper refer to the MNI coordinate system. Subsequently, the spatially normalized images were blurred with a Gaussian filter (FWHM 12 mm) to increase signal-to-noise ratio. All scans were analyzed after normalization to the white matter. The normalization prior to voxel-based statistics was performed using an anatomical mask in MNI space. This normalization was used for all participants to remove the effects of differences in the overall counts. The pixel values were normalized by scaling the activity in each pixel in proportion to the global activity. This ensured that the variance related to the substantially different global activity between high- and low-dose images was stabilized. In this process, the mean global activity of each scan was adjusted to 50. Planned comparisons between the rest and exercise conditions were performed using t statistics for each voxel. These analyses generated statistical parametric maps of the t statistic (SPM {t}), which were subsequently converted to unit normal distribution (SPM {Z}). The estimated final spatial resolution was 19 mm × 21 mm × 18 mm.

The standard deviation for the CV, the ratio of the standard deviation to the mean, in step length during the treadmill walk was large in our sample (mean 7.2 ± 6.0%). However, there was a bimodal distribution around the median value for the CV for step length and it was therefore appropriate to use the median step length for CV as the cut-point dividing the females into low step-length variability (LSV) and high step-length variability (HSV) groups. Student's t test was used to compare age and gait variables between the LSV and HSV groups during treadmill walking. The significance threshold was set at $P < 0.05$. SPSS version 19 (Chicago, IL, USA) was used for statistical analyses.

The locations of relatively activated and deactivated brain areas were identified and listed according to stereotaxic coordinates and visual inspection of the structural MRI provided by SPM8. Significant relative increase (walk > rest) and decrease (rest > walk) in cerebral glucose uptake during the gait condition compared with the rest condition were explored for each group separately. Both relative increases and decreases in glucose metabolism were calculated and considered significant at $P < 0.05$, and were corrected for multiple comparisons using a familywise error (FWE) method [20].

A region of interest (ROI) analysis was used to assess activated and deactivated brain areas during treadmill walking between the HSV and LSV groups, which were interpreted as the relative difference in gait-induced glucose uptake changes between groups. The ROIs were determined on visually apparent regions of relative activation (walk > rest) and deactivation (rest > walk) images for all participants. Glucose metabolism in the ROIs was measured based on the standardized uptake value (SUV), which was defined as follows.

$$\text{SUV} = C/D/w, \quad (3)$$

where C represents the radioactive concentration in the tissue (Bq/mL), D represents the injected dose (Bq), and w represents body mass (g) [21]. FDG dose was adjusted to body weight. Student's t test was used to compare the SUV between the LSV and HSV groups. The significance threshold was set at $P < 0.05$ during between-group comparisons in specific regions. The ROI analysis was performed using the Dr. View software (AJS, Tokyo, Japan). The anatomical designations used to the Talairach Client and MRI atlas of human white matter [22].

3. Results

There was no difference in age between the LSV and the HSV groups (77.4 ± 2.3 versus 78.7 ± 2.2 years; $P = 0.19$) or the following treadmill variables: walking speed (34.7 ± 0.4 versus 34.4 ± 0.5 m/min; $P = 0.26$), cadence (101.4 ± 15.1 versus 96.0 ± 15.7 steps/min; $P = 0.39$), and step length (34.9 ± 5.2 versus 37.4 ± 6.4 cm; $P = 0.31$). The HSV group had a higher step length CV compared to the LSV group (2.7 ± 0.8 versus 11.8 ± 5.5; $P < 0.001$).

The most prominent relative activations during treadmill walking in the LSV group were found in the primary sensorimotor areas (Broadman area (BA) 3 and 4), occipital lobe (BA 17, 18, and 19), and anterior and posterior lobe of the cerebellum compared with the resting condition (Table 1, Fig. 1A). The LSV group did not

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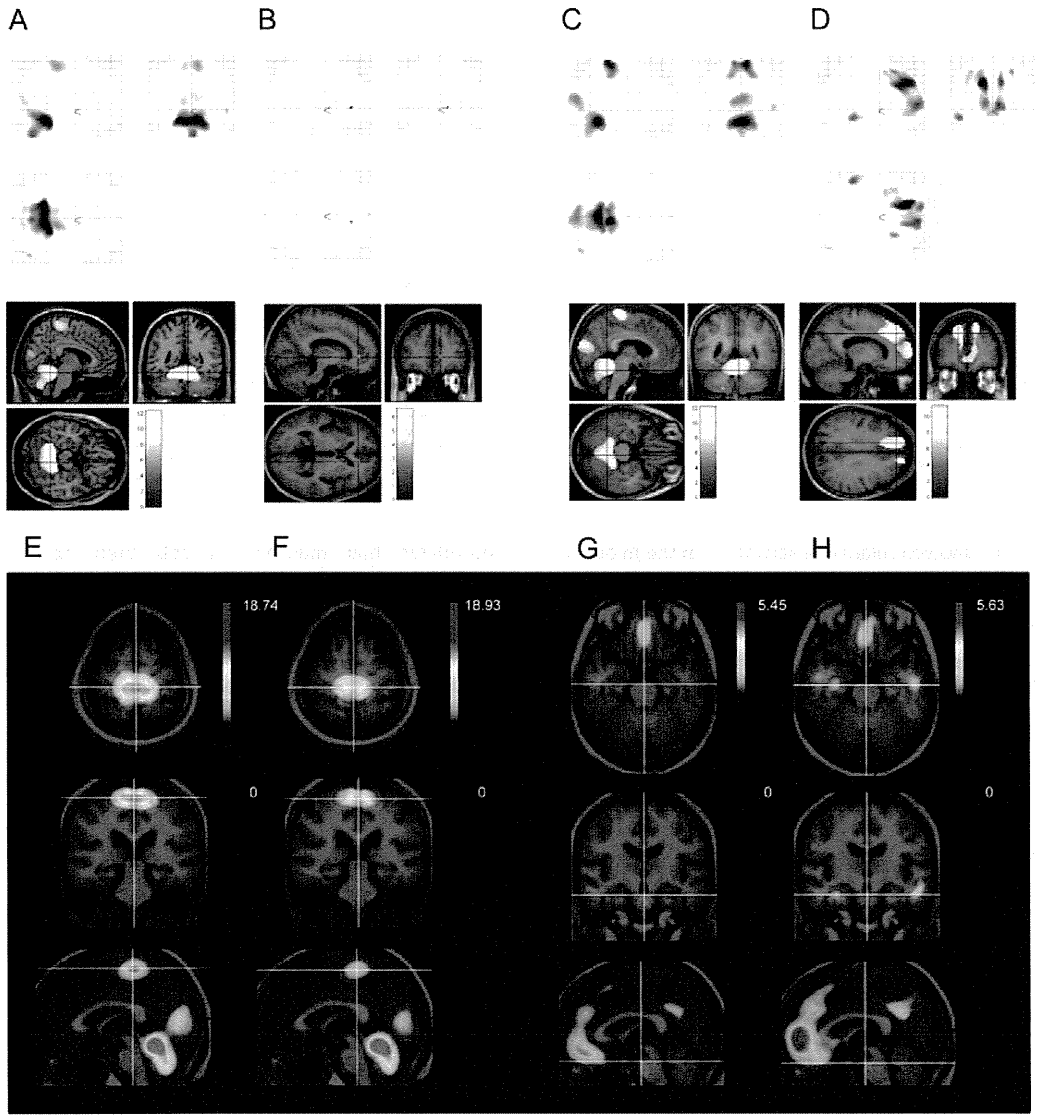

Fig. 1. FDG–PET activations and deactivations during treadmill walking in the LSV and HSV groups. During treadmill walking in the LSV group, activations (A) were prominent in the primary motor areas, visual cortical areas and anterior and posterior lobe of cerebellar. Slight deactivation (B) was found in the right sub-gyral. In the HSV group, activations (C) were prominent in the primary motor areas, visual cortical areas and anterior and posterior lobe of cerebellar. Deactivations (D) were found in the supplementary motor areas (superior and medial frontal cortex, dorsolateral prefrontal cortex). The primary sensorimotor cortex was activated more during treadmill walking versus the resting condition, in the LSV group (E) compared to the HSV group (F). Hippocampus and temporal lobe were deactivated more for treadmill walking versus the resting condition, in the HSV (H) group compared to the LSV group (G).

exhibit prominent relative deactivation during treadmill walking compared with the resting condition (Table 1, Fig. 1B)

The HSV group exhibited marked relative activation in the primary sensorimotor areas (BA 3 and 4), occipital lobe (BA 17, 18, and 19), and anterior and posterior lobe of the cerebellum during treadmill walking compared with the resting condition (Table 2, Fig. 1C). However, the HSV group showed relative deactivation in some regions during treadmill walking. The most prominent relative deactivations during treadmill walking were found in the frontal lobe, including the dorsolateral prefrontal cortex (BA 9 and 46), supplementary motor area (BA 6 and 8), and inferior temporal gyrus (Table 2, Fig. 1D).

Lower panels of Fig. 1 show FDG images of relative activations and deactivations during treadmill walking compared with the resting condition in the participants of the LSV and HSV groups. The SUV uptakes of the relatively activated and deactivated regions are shown in Table 3. The primary sensorimotor areas (BA 3 and 4), occipital lobe (BA 17, 18, and 19), and cerebellum (especially the vermis) were activated during treadmill walking. Relative deactivation of FDG was observed in the orbitofrontal cortex (BA 11), superior frontal gyrus (BA 10), dorsolateral prefrontal cortex (BA 9 and 46), supplementary motor area (BA 6 and 8), middle and superior temporal gyrus white matter, posterior cingulate cortex (BA 31), pons, and hippocampus in all participants. A detailed comparison of the relative activations and deactivations using ROI analysis revealed a more prominent activation of the primary sensorimotor area in the LSV group (Table 3, Fig. 1E) compared with the HSV group (Table 3, Fig. 1F) ($P = 0.02$). The HSV group

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Table 1
FDG activations and deactivations during treadmill walking in the low step-length variability group.

(a) FDG activation during treadmill walking in the low step-length variability group (vs. resting condition)

Cerebral hemispheres	BA	Cluster	Z	T	p	x	y	z
Left cerebellum, anterior lobe, culmen		5196	6.57	12.26	<0.001	−20	−52	−16
Right cerebellum, anterior lobe, culmen			6.46	11.75	<0.001	12	−46	−16
Right cerebellum, posterior lobe, inferior semi-lunar lobule			5.83	9.4	<0.001	4	−68	−38
Right cerebrum, frontal lobe, precentral gyrus		936	5.44	8.22	0.001	10	−30	66
Left cerebrum, parietal lobe, postcentral gyrus	3		4.84	6.69	0.014	−10	−32	66
Right cerebrum, occipital lobe, inferior occipital gyrus	19	39	5.17	7.48	0.004	56	−72	−2
Right cerebellum, posterior lobe		57	4.89	6.8	0.011	20	−50	−58
Left cerebrum, occipital lobe, superior occipital gyrus, cuneus	17	130	4.82	6.63	0.015	−14	−78	12
Right cerebrum, occipital lobe, cuneus	18	147	4.68	6.31	0.027	8	−84	16
Left cerebellum, posterior lobe		4	4.64	6.24	0.03	−24	−84	−46
Left cerebellum, posterior lobe		23	4.63	6.21	0.032	−20	−52	−56
Right cerebrum, occipital lobe, middle or lateral occipital gyrus	19	1	4.54	6.02	0.045	28	−86	38

(b) FDG deactivation during treadmill walking in the low step-length variability group (vs. resting condition)

Cerebral hemispheres	BA	Cluster	Z	T	p	x	y	z
Right cerebrum, frontal lobe, genu of the corpus callosum		5	4.82	6.64	0.015	12	40	0

(Table 3, Fig. 1H) showed relative deactivation in the middle and superior temporal gyrus white matter ($P = 0.03$) and hippocampus ($P = 0.03$) during treadmill walking compared with resting than did the LSV group (Table 3, Fig. 1G). There were no significant differences in occipital lobe, cerebellum, frontal lobe, posterior cingulate cortex, and pons between groups.

4. Discussion

This study examined changes in whole brain glucose metabolism using FDG-PET during rest and unaccustomed treadmill walking in healthy elderly females, classified as either low or high step-length variability walkers. The main findings of the study were that females with high step-length variability showed relative deactivations in the supplementary motor areas and dorsolateral prefrontal cortex compared to rest and that females with low step-length variability exhibited greater relative activations in the primary motor area during treadmill walking compared to the HSV group. The HSV group showed greater relative deactivations in the temporal lobe, especially in the hippocampus, during treadmill walking compared with the LSV group.

Hanakawa [23] proposed a hypothesis regarding the neural mechanisms that control human bipedal gait. This author postulated that multiple channels from the basal ganglia–thalamocortical system and basal ganglia–brainstem system are involved in the regulation of the central pattern generator (CPG) in the spinal cord (Fig. 2). In the present study, the most prominent relative activations during treadmill walking were found in the primary sensorimotor areas, occipital lobe, and cerebellar areas for both groups. The primary motor area projects to the spinal cord through the corticospinal tract, and it is believed that the primary motor area is involved in the precise control of limb movement during walking. The coordination of limb and trunk movements to adjust for a shift in the center of gravity associated with locomotion may be one of the primary functions of the cerebellum in gait control. Previous neuroimaging experiments have shown that the cerebellar vermis and the anteromedial part of the cerebellar hemispheres are bilaterally activated during walking in healthy individuals [9,11,12]. The cerebellum is able to make immediate alterations in ongoing movement patterns [24]. It functions as a real-time sensory processing device and modulates motor responses in a reactive or feedback manner based on sensory perturbations [25].

Our findings also suggest that the cerebellum plays an important role in gait adaptation to unfamiliar environments, such as walking on a treadmill. The occipital lobe, including the

Table 2
FDG activations and deactivations during treadmill walking in the high step-length variability group.

(a) FDG activation during treadmill walking in the high step-length variability group (vs. resting condition)

Cerebral hemispheres	BA	Cluster	Z	T	p	x	y	z
Right cerebellum, anterior lobe, culmen		3715	6.54	12.12	<0.001	0	−50	−18
Right cerebrum, parietal lobe, postcentral gyrus	6	1878	6.37	11.38	<0.001	8	−32	72
Left cerebrum, parietal lobe, postcentral gyrus	3		5.75	9.16	<0.001	−10	−34	72
Left cerebrum, parietal lobe, postcentral gyrus white matter			5.4	8.09	0.001	−14	−28	54
Right cerebrum, occipital lobe, cuneus		1402	5.52	8.46	0.001	2	−84	18
Left cerebrum, occipital lobe, cuneus			5.47	8.29	0.001	−6	−82	14
Right cerebrum, occipital lobe, middle or lateral occipital gyrus		60	5.06	7.2	0.005	52	−78	4
Left cerebellum, posterior lobe		40	4.74	6.45	0.017	−22	−46	−52
Right cerebellum, posterior lobe		7	4.67	6.3	0.022	36	−84	−40
Right cerebrum, occipital lobe, middle or lateral occipital gyrus	17	3	4.52	5.99	0.039	26	−100	−12

(b) FDG deactivation during treadmill walking in the high step-length variability group (vs. resting condition)

Cerebral hemispheres	BA	Cluster	Z	T	p	x	y	z
Left cerebrum, frontal lobe, superior frontal gyrus		5131	6.31	11.14	<0.001	−18	46	40
Right cerebrum, frontal lobe, superior frontal gyrus white matter			5.74	9.13	<0.001	10	60	6
Right cerebrum, frontal lobe, superior frontal gyrus	8		5.7	8.98	<0.001	12	54	40
Left cerebrum, temporal lobe, inferior temporal gyrus		397	5.62	8.74	<0.001	−52	−44	−14
Right cerebrum, frontal lobe, middle frontal gyrus	6	113	5.38	8.04	0.001	30	22	58

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