

Association between latent gait patterns and reduced femoral neck bone mineral density in community-dwelling older women: a cross-sectional study

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Research Article

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Abstract

Background

There are limitations in identifying the comprehensive gait patterns associated with reduced bone mineral density. The main purpose of this study was to examine the association between latent gait patterns and femoral neck bone mineral density in community-dwelling older women.

Methods

The participants were women aged 60 years or older who were using senior welfare facilities in Suwon-si, Gyeonggi-do. Gait patterns were identified through the latent profile analysis based on four variables (gait speed, step length difference, stride-length variability, and walk ratio) measured during usual-speed and fast-speed gait. Then, participants were classified in the normal ($T\text{-score} \geq -1.0$), osteopenia ($-1.0 > T\text{-score} > -2.5$), or osteoporosis group ($T\text{-score} \leq -2.5$) based on the T-score of femoral neck bone mineral density measured by dual-energy X-ray absorptiometry.

Results

This study included 179 women. The gait pattern analysis identified a stable gait pattern and an unstable gait pattern during usual gait. When the relative risk of osteopenia and osteoporosis according to the gait pattern was subsequently calculated, the unstable gait group (odds ratio [OR] = 3.335, 95% confidence interval = 1.066–10.431, $p = 0.038$) showed a significantly higher risk of osteoporosis than the stable group (OR = 1, reference).

Conclusions

These findings suggest that an unstable gait pattern combining slow gait speed, bilateral step length asymmetry, and high stride-length variability may represent a gait phenotype associated with osteoporosis in older women. Once the reproducibility and clinical classification criteria of this gait phenotype are established, it is expected to be useful as baseline data for screening older adults with a high likelihood of osteoporosis.

Background

Osteoporosis is defined as a disease in which bone strength is weakened and susceptibility to fracture increases due to a loss of bone mass and changes in the microarchitecture resulting from the disruption of bone homeostasis [1]. In particular, older women are susceptible to its onset, with increased bone resorption due to aging and the postmenopausal decrease in estrogen levels as the main causes [2]. Indeed, according to a report by the Korean Society for Bone and Mineral Research, the prevalences of

osteoporosis among older Korean men are 7.5% in those in their 60s and 18.0% in those aged 70 years or older, whereas the corresponding figures for women are 36.6% and 68.5%, indicating a markedly higher prevalence in women than in men [3]. Considering the current trend of population aging in Korea, the number of patients with osteoporosis is expected to continue to increase. Thus, the need for osteoporosis prevention and management strategies centered on older women has been raised at the societal level [3].

Well-known risk factors for the onset of osteoporosis include genetic factors, such as age, sex, family history, and early menopause; lifestyle factors, such as smoking, excessive drinking, nutritional imbalance, and lack of exercise; and disease-related factors, such as rheumatoid arthritis and metabolic syndrome [4, 5]. These risk factors increase the ratio of bone resorption to bone formation, thereby causing an imbalance in bone metabolism and consequently increasing the risk of one developing osteoporosis [6, 7]. Additionally, osteoporosis has been reported to more than double the risk of initial and subsequent fractures compared with non-osteoporosis, and fractures not only to lead to various secondary conditions, such as cardiovascular disease and dementia, but also to increase the risk of premature death [8–13]. As no clear subjective symptoms of osteoporosis appear until a fracture occurs, early detection is often difficult; therefore, monitoring individuals through periodic bone mineral density testing is recommended for fracture prevention and early disease detection and management [7]. However, bone mineral density testing based on dual-energy X-ray absorptiometry (DXA), which is currently used as the standard diagnostic method in clinical practice, entails high testing costs, limited accessibility, and concerns about radiation exposure with repeated measurements, despite the advantage of providing high accuracy [14].

Gait is a quantitative indicator that comprehensively reflects body composition and physical function in older age, including muscle mass, muscle strength, and balance ability [15]. Numerous studies have reported that gait is closely associated with reduced bone mineral density, and its potential use as a non-invasive screening indicator for osteoporosis has attracted attention [16–19]. Specifically, in Lindsey et al.'s study (2005), which analyzed the association between spatiotemporal gait parameters and bone mineral density in postmenopausal women, gait speed and step length during usual and fast walking were identified as key variables that were significantly associated with bone mineral density [16]. Moreover, Sung's study (2018) reported that step length asymmetry—characterized by a shorter step length of the non-dominant leg relative to that of the dominant leg—was significantly associated with reduced bone mineral density in older adults [17]. Further, gait variability, which reflects the stability and consistency of gait across repeated gait cycles, is a useful variable for identifying reduced bone mineral density in postmenopausal women [18], and a decrease in the walk ratio, which reflects gait automaticity and neuromotor control and is characterized by a short step length and a high cadence, was significantly associated with an increased risk of osteoporosis in older women [19].

Most previous studies investigating the association between gait and bone mineral density have focused on the role of single variables constituting gait, despite the fact that gait is a complex movement formed through the interaction of temporal and spatial characteristics. Consequently, there are limitations in

identifying the comprehensive gait patterns associated with reduced bone mineral density. Considering this, identifying individuals' gait patterns based on combinations of spatiotemporal gait parameters and analyzing the association between these gait patterns and bone mineral density would allow a more specific understanding of the gait characteristics associated with reduced bone mineral density that are difficult to identify using single gait variables alone. Accordingly, this study aimed to derive gait patterns using the latent profile analysis in community-dwelling older women and analyze the association between these gait patterns and femoral neck bone mineral density.

Methods

Study design and participants

This study initially recruited 243 community-dwelling older women aged 60 years or older who were using senior welfare facilities located in Suwon-si, Gyeonggi-do. Prior to participation, all participants were provided with detailed information regarding the purpose, methods, and procedures of the study, and only those who voluntarily agreed to participate were enrolled. Of the 243 initially recruited participants, 64 were excluded: 16 because they refused bone mineral density measurement or had missing bone mineral density data, 32 because gait assessment could not be performed or gait data were missing, and 16 because of missing data for other covariates. Consequently, data from 179 participants were included in the final analysis. This study was conducted in accordance with the approval of the Institutional Review Board of Changwon National University (IRB No. 7001066-202506-HR-041).

Body composition and anthropometric characteristics

Participants' height and weight were measured in an upright standing position using an automatic height and weight measuring device (DS-102; Jenix, Seoul, Korea), and the body mass index was calculated by applying the measured height and weight to the following formula: $\text{weight (kg)} / \text{height (m}^2\text{)}$. Subsequently, the appendicular muscle mass and femoral neck bone mineral density were measured using a device based on the principle of DXA (Lunar DPX Pro; GE Medical Systems Lunar, Madison, WI, USA), and the appendicular muscle mass index was calculated by applying the measured appendicular muscle mass to the following formula: $\text{appendicular muscle mass (kg)} / \text{height (m}^2\text{)}$. Finally, using an anthropometric tape measure, the waist circumference was measured in centimeters at the midpoint between the lowest rib and the upper margin of the iliac crest.

Definitions of osteopenia and osteoporosis

Based on the T-score of femoral neck bone mineral density measured in the preceding step, participants were classified in the normal, osteopenia, or osteoporosis group as follows, in accordance with the

osteoporosis diagnostic criteria presented by the World Health Organization [20] (normal, T-score ≥ 1.0 ; osteopenia, $-1.0 > \text{T-score} > -2.5$; and osteoporosis, T-score ≤ -2.5).

Gait measurement

A total walking distance of 10 m was set up, and the 5-m section remaining after excluding the initial 2.5-m acceleration section and the final 2.5-m deceleration section was designated as the section for measuring gait function [21]. Then, gait function during usual gait and fast gait was measured three times each using a gait analyzer (Optogait; Microgait, Bolzano, Italy). Based on the measured gait function and with reference to previous research [22], four variables representing gait characteristics in older age were used as the variables for identifying gait patterns. Specifically, gait speed (representing gait ability), bilateral step length difference (indicating gait symmetry), stride-length variability (representing gait regularity), and walk ratio (indicating gait coordination) were used as the variables for identifying gait patterns. The gait speed and bilateral step length difference were obtained from the indices analyzed by the gait analyzer, and stride-length variability and walk ratio were calculated using the following formulas [22, 23].

1. Stride-length variability (%) = Standard deviation of stride-length / Mean stride-length $\cdot 100$
2. Walk ratio (cm/steps/min) = Height-adjusted step / Height-adjusted cadence $\cdot 100$

Covariates

Current age, age at menopause, educational level, and marital status were surveyed as socio-demographic factors, and smoking, excessive drinking, physical inactivity, cognitive function, fall experience, and the number of cardiovascular disease risk factors were surveyed as health-related factors. The educational level was classified as elementary school graduation or lower, middle or high school graduation, and junior college graduation or higher, and marital status was classified as married and divorced, widowed, or separated. Smoking was defined as currently smoking or having a lifetime smoking history of five packs or more [24], and drinking was classified according to whether the participant had consumed alcohol within the past year. Physical inactivity was defined as a weekly physical activity level of 600 MET or less, as surveyed by the short-form International Physical Activity Questionnaire [25]; and fall experience was defined as having experienced a fall within the past year. Finally, the number of cardiovascular disease risk factors was assessed using the pre-participation risk assessment presented by the American College of Sports Medicine [26].

Statistical analysis

Continuous data are presented as mean and SD, and categorical data are presented as frequency (n) and percentage (%). First, the latent profile analysis was performed to identify gait patterns during usual gait and fast gait. Such analysis is an analytic method that can identify homogeneous and heterogeneous

subgroups within a population on the basis of continuous variables, and the optimal number of patterns can be identified through model fit indices, such as log-likelihood (ll), Bayesian Information Criterion (BIC), Akaike Information Criterion (AIC), entropy, P > Lo-Mendell-Rubin test result (P > LMR), and class probability, together with theoretical considerations. Specifically, ll is an index of the explanatory power of the model, and BIC and AIC are indices of model fit; a higher ll value indicates greater explanatory power, whereas lower BIC and AIC values indicate better fit. Entropy is an index of how accurately participants are classified into each group, with a value of ≥ 0.8 recommended; P > LMR indicates whether a model with k classes is more appropriate than a model with k – 1 classes, and a significance probability of P < .05 provides grounds for model selection. Finally, class probability is the estimated proportion accounted for by each group and is used as an index for confirming that there are no small groups accounting for < 10% [27]. On the basis of these criteria and with reference to previous research [27], this study identified latent gait patterns based on four variables representing the clinical aspects of gait ability, symmetry, regularity, and coordination in older age (gait speed, step length difference, stride-length variability, and walk ratio).

After identifying the gait patterns, differences in the continuous and categorical variables according to the gait pattern were compared using the independent-samples t-tests and cross-tabulation analysis, and odds ratios (ORs) and 95% confidence intervals (CIs) for osteopenia and osteoporosis according to the gait pattern were calculated using the binary logistic regression analysis. All the data analyses were performed using STATA (version 18.0; StataCorp LLC, College Station, TX, USA)), and the statistical significance level for hypothesis testing was set at $\alpha = .05$.

Results

Descriptive results

Table 1 presents the characteristics of the study participants. The mean age of the participants was 73.8 years (SD = 6.1). Regarding bone health status, 58.1% of the participants had osteopenia and 21.2% had osteoporosis.

Table 1
Characteristics of the study participants

Variables	Total (n = 179/100.0%)
Socio-demographic factors	
Age (years)	73.8 ± 6.1
Menopause age (years)	49.8 ± 5.2
Education, n (%)	
Lower than elementary school	114 (63.7)
Middle/high school	60 (33.5)
Junior college graduation or higher	5 (2.8)
Marital status, n (%)	
Married	76 (42.5)
Widowed/divorced	103 (57.5)
Anthropometric measurement	
Body mass index (kg/m ²)	24.9 ± 3.2
Waist circumference (cm)	96.4 ± 14.5
ASM index (kg/m ²)	5.8 ± 0.6
Health-related parameters	
Smoking, n (%)	17 (9.5)
Drinking, n (%)	6 (3.4)
Inactivity, n (%)	83 (46.4)
Fall experience (%)	43 (24.0)
CVD risk factors	3.4 ± 1.1
Bone health parameters	
Femoral neck BMD (g/cm ²)	0.727 ± 0.107
Femoral neck BMD T-score	-1.794 ± 0.892
Bone health status, n (%)	
Values are presented as mean ± standard deviation or n (%). ASM: appendicular skeletal muscle mass, CVD: cardiovascular disease, BMD: bone mineral density	

Variables	Total (n = 179/100.0%)
Socio-demographic factors	
Normal	37 (20.7)
Osteopenia	104 (58.1)
Osteoporosis	38 (21.2)
Gait parameters	
Usual gait speed (m/sec)	1.2 ± 0.2
Usual step length difference (cm)	3.2 ± 3.0
Usual stride length variability (%)	3.5 ± 2.4
Usual walk ratio (cm/steps/min)	50.2 ± 9.6
Fast gait speed (m/sec)	1.6 ± 1.3
Fast step length difference (cm)	3.5 ± 3.4
Fast stride-length variability (%)	4.1 ± 6.6
Fast walk ratio (cm/steps/min)	46.7 ± 6.7
Values are presented as mean ± standard deviation or n (%). ASM: appendicular skeletal muscle mass, CVD: cardiovascular disease, BMD: bone mineral density	

Gait patterns

The results of analyzing the gait patterns of the 179 older women are presented in Table 2. Under the usual gait condition, Model 3 had the highest *ll* value and the lowest AIC and BIC values, indicating the best model fit and explanatory adequacy. Additionally, entropy was ≥ 0.8 , indicating good classification, and the LMR test showed a significant difference (Model 3 versus [vs.] Model 2, $P < 0.001$), confirming model improvement with an increased number of classes. However, in Model 3, the assignment proportion of one latent profile was $< 10\%$ in the class probability, and the model was therefore judged to have low interpretability. By contrast, Model 2 showed good classification accuracy with an entropy of ≥ 0.8 , satisfied the LMR test (Model 2 vs. Model 1, $P < 0.001$), and had assignment proportions of $\geq 10\%$ for all latent profiles; hence, it was selected as the final model.

Table 2
Fitting indices of the latent profile models for gait patterns in older women

Classes	II	AIC	BIC	Entropy	P > LMR	Class Probability
Usual gait						
Model 1	-1.178.55	2,373.10	2,399.80			
Model 2	-1,152.56	2,331.13	2,374.52	0.880	< 0.001	0.131/0.869
Model 3	-1,016.06	2,068.11	2,128.19	0.925	< 0.001	0.131/0.864/0.005
Fast gait						
Model 1	-1,178.55	2,373.10	2,399.80			
Model 2	-1,041.04	2,108.09	2,151.48	1.000	< 0.001	0.005/0.995
Model 3	-885.20	1,806.39	1,866.47	1.000	< 0.001	0.024/0.971/0.005
BIC: Bayesian Information Criterion, AIC: Akaike Information Criterion, P > LMR: P > Lo-Mendell-Rubin test result						

Under the fast gait condition, Model 3 showed the best explanatory power and fit and satisfied the entropy and LMR test criteria. However, in Models 3 and 2, one latent profile accounted for < 10%, making it difficult to identify an interpretable latent profile structure. Therefore, under the fast gait condition, no latent gait pattern satisfying statistical fit and interpretability was identified.

The gait patterns under the usual gait condition are presented in Fig. 1. Specifically, one of the two groups was observed to have a high gait speed, a small difference in step length between the two feet, and low stride-length variability. By contrast, the other group had a low gait speed, a large difference in step length between the two feet, and high stride-length variability. Based on these characteristics, the former group was named the Stable group and the latter group the Unstable group.

Comparison of variables according to the gait patterns

The results of comparing the variables according to gait pattern under the usual gait condition are presented in Table 3. The Unstable group had a significantly higher proportion of divorced and widowed participants than the Stable group. By contrast, no significant differences were found for the other variables.

Table 3
Characteristics of the study participants in the Stable and Unstable groups

Variables	Stable (n = 154/86.0%)	Unstable (n = 25/14.0%)	P-value
Socio-demographic factors			
Age (years)	73.6 ± 5.9	75.4 ± 6.6	0.168
Menopause age (years)	50.0 ± 5.0	48.3 ± 6.2	0.135
Education, n (%)			0.535
Lower than elementary school	96 (62.3)	18 (72.0)	
Middle/high school	54 (35.1)	6 (24.0)	
Junior college graduation or higher	4 (2.6)	1 (4.0)	
Marital status, n (%)			0.044
Married	70 (45.5)	6 (24.0)	
Widowed/divorced	84 (54.5)	19 (76.0)	
Anthropometric measurement			
Body mass index (kg/m ²)	24.8 ± 3.3	25.0 ± 2.5	0.865
Waist circumference (cm)	96.6 ± 14.7	95.1 ± 13.0	0.615
ASM index (kg/m ²)	5.8 ± 0.6	5.8 ± 0.5	0.533
Femoral neck BMD (g/cm ²)	0.735 ± 0.105	0.676 ± 0.107	0.009
Femoral neck BMD T-score	-1.725 ± 0.877	-2.224 ± 0.883	0.009
Health-related parameters			
Smoking, n (%)	15 (9.7)	2 (8.0)	0.783
Drinking, n (%)	5 (3.2)	1 (4.0)	0.846
Inactivity, n (%)	69 (44.8)	14 (56.0)	0.298
Fall experience (%)	35 (22.7)	8 (32.0)	0.314
CVD risk factors	3.4 ± 1.0	3.5 ± 1.1	0.476
Bone health status, n (%)			0.048
Normal	36 (23.4)	2 (8.0)	
Values are presented as mean ± standard deviation or n (%). ASM: appendicular skeletal muscle mass, CVD: cardiovascular disease, BMD: bone mineral density			

Variables	Stable (n = 154/86.0%)	Unstable (n = 25/14.0%)	P-value
Socio-demographic factors			
Osteopenia	91 (59.1)	14 (56.0)	
Osteoporosis	27 (17.5)	9 (36.0)	
Values are presented as mean $\pm$ standard deviation or n (%). ASM: appendicular skeletal muscle mass, CVD: cardiovascular disease, BMD: bone mineral density			

Comparison of the bone mineral density and bone health status according to the gait patterns

The results of comparing the bone mineral density and bone health status according to the gait pattern under the usual gait condition are presented in Table 4. Compared with the Unstable group, the Stable group had significantly higher total hip bone mineral density, total hip bone mineral density T-score, femoral neck bone mineral density, and femoral neck bone mineral density T-score, and a significantly lower prevalence of osteoporosis.

Table 4
ORs and 95% CIs of low bone mineral density according to the usual gait pattern

Variables	Model 1		Model 2	
	OR (95% CI)	P-value	OR (95% CI)	P-value
Normal vs. Osteopenia				
Stable	1 (reference)		1 (reference)	
Unstable	2.769 (0.599–12.802)	0.192	4.244 (0.699–25.751)	0.116
Osteopenia vs. Osteoporosis				
Stable	1 (reference)		1 (reference)	
Unstable	2.167 (0.845–5.553)	0.107	2.640 (0.825–8.445)	0.102
Normal + Osteopenia vs. Osteoporosis				
Stable	1 (reference)		1 (reference)	
Unstable	2.646 (1.058–6.614)	0.037	3.335 (1.066–10.431)	0.038
OR: odds ratio, CI: confidence interval, ASM: appendicular skeletal muscle mass, CVD: cardiovascular disease, vs.: versus				
Model 1: unadjusted.				
Model 2: adjusted for age, age at menopause, education level, marital status, body mass index, ASM index, smoking, excessive alcohol use, inactivity, fall experience, and CVD risk factors.				

ORs and 95% CIs for osteopenia and osteoporosis according to the gait patterns

The results of analyzing the ORs for osteopenia and osteoporosis according to the gait pattern under the usual gait condition are presented in Table 4. First, when the OR for progression from normal to osteopenia was calculated, no significant difference was found between the Stable and Unstable groups in either Model 1, which was not adjusted for covariates, or Model 2, which was adjusted for socio-demographic factors, body composition and anthropometric factors, and health-related factors. Likewise, when the OR for progression from osteopenia to osteoporosis was calculated, no significant difference was found between the Stable and Unstable groups in either Model 1 or 2. By contrast, when the OR for osteoporosis from the normal or osteopenia stage was calculated, the Unstable group showed a significantly higher odds of osteoporosis than the Stable group in Models 1 and 2.

Discussion

The main purpose of this study was to derive latent gait patterns in 179 community-dwelling older women aged 60 years or older and then analyze their association with femoral neck bone mineral density. The study identified two patterns during usual gait. Specifically, we identified the Stable group, showing a stable gait pattern, and the Unstable group, showing a contrasting unstable gait pattern. Moreover, when the relative risk of osteopenia and osteoporosis was calculated after deriving the gait patterns, the risk of osteoporosis was approximately 3.3 times higher in the Unstable group than in the Stable group.

Gait is the most fundamental means of enabling independent daily living and mobility in humans, and it is a movement that requires the complex integration of various physical functions, such as muscle strength, balance ability, coordination, and neuromuscular control [22, 28]. Therefore, declines in physical function due to aging and disease can manifest as changes in gait characteristics, and gait patterns that comprehensively reflect these characteristics can have important clinical significance for understanding one's health status [22, 29]. However, previous studies identifying gait characteristics related to health status in older age have focused mainly on examining relationships with single variables constituting gait and are therefore limited in identifying comprehensive gait patterns related to health status [29]. Thus, identifying gait patterns that reflect diverse gait characteristics is expected to provide more specific information for assessing one's health status than single variables. Accordingly, to examine the association of gait pattern with osteoporosis in community-dwelling older women, this study first performed the latent profile analysis based on four variables reflecting different gait characteristics to derive the gait patterns. Consequently, two patterns were identified under the usual gait condition: a stable gait pattern with a fast gait speed, symmetrical bilateral step length, and low stride-length variability; and an unstable gait pattern with a slow gait speed, asymmetrical bilateral step length, and high stride-length variability. Similarly, a study of older adults in Germany that derived gait patterns based on four variables similar to those in the present study under the usual gait condition identified two

groups showing clear differences in gait speed, step width difference, stride-length variability, and walk ratio [29]. Judging from the results of this study and previous research [30], gait in older adults can therefore be classified into patterns combining diverse gait characteristics beyond a single indicator, and each pattern shows clear differences in the overall gait performance characteristics. In this context, considering that gait is a movement arising from the complex performance of physical functions, gait patterns may also differ according to the health status of older adults. Therefore, analyzing gait patterns is expected to be a more useful approach than analyzing individual gait variables alone for comprehensively and specifically identifying the gait characteristics related to older adults' health status, and the results of the current study and previous research support this possibility.

When the relative risk of reduced bone mineral density was calculated after identifying the gait patterns, the Unstable group had a significantly higher risk of osteoporosis than the Stable group. These findings extend those of previous research reporting that reduced bone mineral density in postmenopausal women and older adults is associated with individual gait characteristics, such as gait speed, gait asymmetry, and gait variability measured under the usual gait condition. They suggest that the gait characteristics associated with reduced bone mineral density may appear not only individually but also as a single pattern, and that an unstable gait pattern combining slow gait speed, bilateral step length asymmetry, and high stride-length variability may constitute a gait phenotype associated with osteoporosis [17, 18, 30]. Accordingly, if the association between the gait pattern and osteoporosis identified in this study is reproducible in other older adult populations and empirical criteria for classifying the unstable gait phenotype are established, the gait phenotype may serve clinically as a non-invasive, auxiliary means of screening older adults with a high likelihood of osteoporosis and referring them for DXA examination. Furthermore, the fact that this study was able to identify the gait characteristics associated with osteoporosis as a pattern in which not only decreased gait speed but also increased step length asymmetry and stride-length variability appear together is expected to provide baseline data for establishing exercise and gait intervention strategies for older adults with osteoporosis.

The association between the unstable gait pattern and osteoporosis observed in this study can be explained on the basis of previous studies reporting changes in the biomechanical function of gait that accompany reduced bone mineral density. First, postmenopausal women with reduced bone mineral density at the femoral neck and lumbar spine show decreased power generation and absorption at the hip and ankle, resulting in reduced gait propulsion and stability [31]. Additionally, older women with reduced femoral neck bone mineral density show differences in left–right trunk movement during gait [32]. Taking the findings of these previous studies together, it can be inferred that the reduced gait propulsion and stability and the imbalance in left–right trunk movement accompanying reduced bone mineral density may manifest as characteristics such as decreased gait speed, step length asymmetry, and increased stride-length variability, which may provide evidence supporting the association between the unstable gait pattern and osteoporosis identified here.

However, this study has some limitations, as follows. As a cross-sectional study, this study cannot establish a causal relationship between the gait pattern and osteoporosis. Therefore, it cannot be clearly determined whether the unstable gait pattern identified in this study is a consequence of reduced femoral neck bone mineral density or whether the two characteristics appear together as part of a common decline in physical function due to aging. Since the study participants were limited to community-dwelling older women aged 60 years or older who used senior welfare facilities in a specific region, there are limitations in generalizing the results to men, other age groups, or older adults residing in other regions. Factors that may influence gait characteristics, such as muscle strength, muscle mass, and musculoskeletal pain, were not sufficiently considered. Therefore, future studies need to assess these factors together to more clearly establish the independent association between osteoporosis and the gait pattern. Finally, the stable and unstable gait patterns identified in this study were derived exploratorily through the latent profile analysis based on a single group of participants, and it was not confirmed whether the same or similar gait patterns are reproduced in other older adult populations. Therefore, the reproducibility of the gait phenotype derived here and its association with osteoporosis need to be verified in diverse older adult populations.

Conclusions

In community-dwelling older women aged 60 years or older, a stable gait pattern and an unstable gait pattern were identified during usual gait, and the unstable gait pattern showed a significantly higher relative risk of osteoporosis than the stable gait pattern. These findings suggest that an unstable gait pattern combining slow gait speed, bilateral step length asymmetry, and high stride-length variability may represent a gait phenotype associated with osteoporosis in older women. Accordingly, once the reproducibility and clinical classification criteria of this gait phenotype are established, it is expected to be useful as baseline data for screening older adults with a high likelihood of osteoporosis, referring them for DXA examination, and establishing exercise and gait intervention strategies for them. Considering the aforementioned limitations, future research should verify the reproducibility of the gait phenotype identified in this study in diverse older adult populations and establish the causal relationship between the gait pattern and osteoporosis through prospective longitudinal studies.

Abbreviations

BMD: bone mineral density, DXA: dual-energy X-ray absorptiometry, SD: standard deviation; CI: confidence interval, OR: odds ratio, ll: log-likelihood, BIC: Bayesian Information Criterion, AIC: Akaike Information Criterion, P > LMR: P > Lo-Mendell-Rubin test result

Declarations

Ethics approval and consent to participate

Before the study was conducted, the purpose, methods, and procedures were explained in detail to all participants, and only those who voluntarily agreed to participate were included. Written informed consent was obtained from all participants prior to participation. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board of Changwon National University (approval number: IRB-7001066-202506-HR-041).

Clinical trial number

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The data used during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

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Authors' contributions

Conceptualization, M Kim, and I Lee.; methodology, M Kim, and I Lee; formal analysis, M Kim, and J Kim; investigation, M Kim, J Kim, and I Lee.; data curation, M Kim, J Kim, and I Lee.; writing – original draft preparation, M Kim, J Kim, and I Lee.; writing – review and editing, M Kim, J Kim, and I Lee.; visualization, M Kim.; supervision, M Kim, and I Lee.; project administration, M Kim, and I Lee.; funding acquisition, M Kim.

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Figures

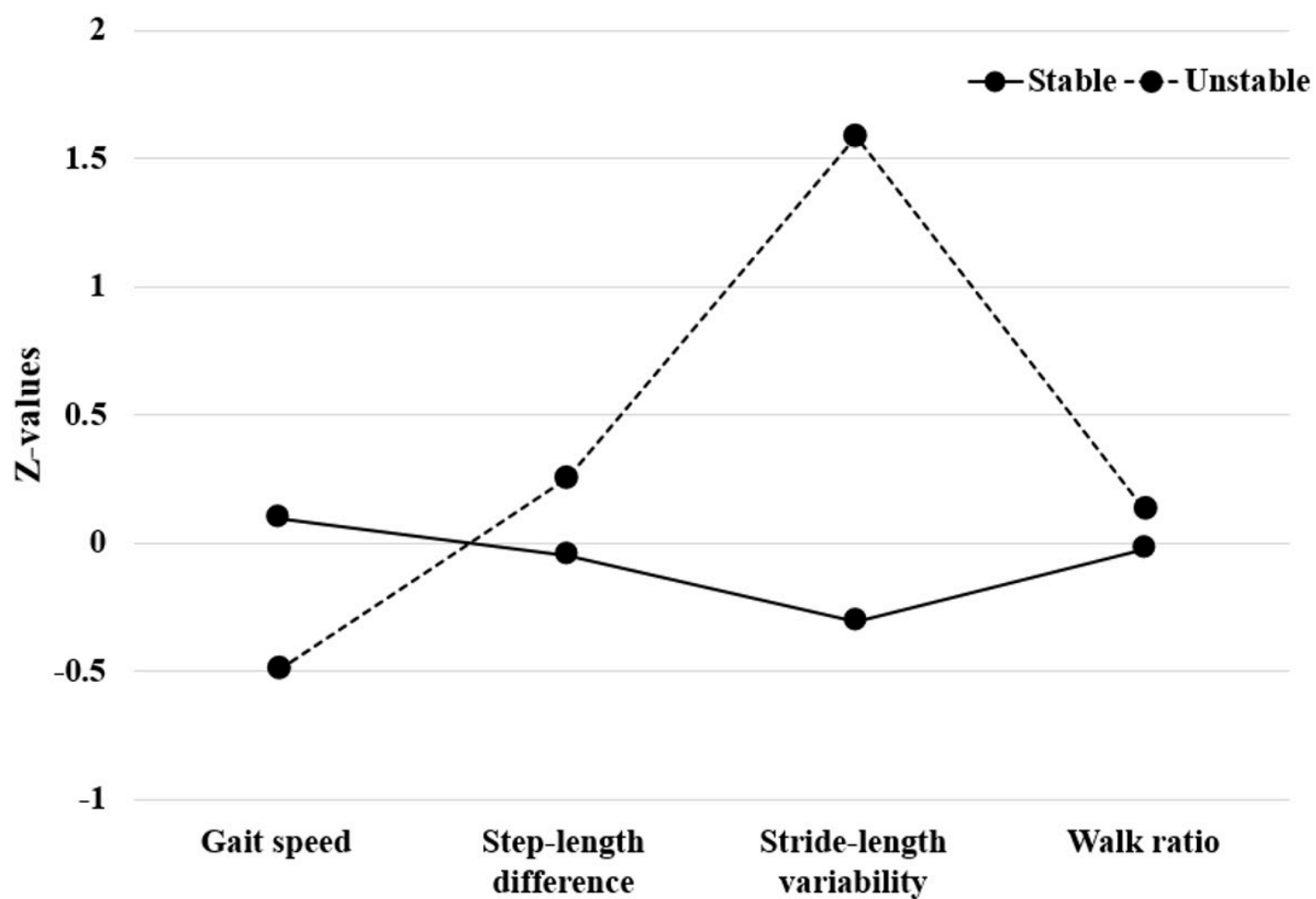


Figure 1

The two gait patterns under the usual gait speed condition.

Note: All variables were standardized as z-scores to improve visual presentation.