SUCCESSFUL locomotion is thought to require stability during gait. During normal walking, control of trunk movement is prioritized and contributes to head stability to maintain gait stability (1). Age-related gait changes among older adults induce trunk instability, which is reflected in reduced smoothness of trunk motion (2,3), and is more pronounced during more challenging walking tasks than during normal walking (4). Walking is a motor task that requires consecutive movement and adaptability to a changing environment. Successful locomotion not only requires input from the neuromuscular system but also from high-order cognitive systems such as executive function.

The performance of executive function has been associated with gait performance, and this relationship is stronger during more challenging walking tasks such as dual-task walking (5,6,7). To investigate the cognitive demands of walking, dual-task walking has been researched, for example, walking while performing a cognitive task or walking while talking. Dual-task walking markedly increased the variability of lower limb gait variables in older adults with cognitive impairment (8,9) and even in healthy older adults (10,11,12). Additionally, dual-task walking affected trunk movement in healthy older adults (7,13,14,15). Cognitive demands during dual-task walking affect spatiotemporal gait parameters. Dual-task–related changes (DTC) in gait variables correlate with both mobility and cognitive function in healthy older adults with normal gait performance (5). Moreover, dual-task training involving mobility tasks improved not only mobility function but also cognitive function (16, 17). Thus, dual-task walking may require and activate more multidomain neural resources in the brain than normal walking.

### Background

Dual-task walking is believed to be more cognitively demanding than normal walking and alters trunk movement among older adults. However, the possible association between brain atrophy and spatiotemporal gait parameters, particularly during dual-task walking, is poorly understood. In this study, we examined the relationship between dual-task walking and brain atrophy.

### Methods

One hundred ten elderly adults (aged 65–94 years, women n = 55) underwent magnetic resonance imaging scanning and gait experiments under normal and dual-task walking conditions. Linear accelerations of the trunk were measured in vertical, anteroposterior, and mediolateral directions using a triaxial accelerometer attached to the lower trunk. Gait speed, stride length, and cadence were recorded. The harmonic ratio, a measure of trunk stability, was computed separately in each direction to evaluate the smoothness of trunk movement during walking. Brain atrophy was quantitatively assessed using magnetic resonance image data.

### Results

Gait speed, stride length, cadence, and harmonic ratio in all directions were lower in dual-task walking than in normal walking ($p < .05$). The dual-task–related changes in harmonic ratio were independently correlated with brain atrophy adjusted for subject characteristics only in the vertical direction ($p < .05$).

### Conclusions

Our findings support the hypothesis that dual-task walking is more cognitively demanding than normal walking. Decreased trunk stability during dual-task walking is associated with brain atrophy. Additional studies are necessary to elucidate the effects of regional brain atrophy on the control of walking.

### Key Words:
Brain atrophy—Gait analysis—Dual-task walking—Acceleration.
Emerging evidence suggests that age-related changes in the brain are linked to mobility deficits. Examples of these age-related changes include structural changes and changes to the biochemistry in the brain (18). Changes in the white matter (19,20,21) or the volume of gray matter (21,22,23), that is, macrostructural changes seen on magnetic resonance images (MRI), are also associated with changes in gait parameters. MRI-based measures of atrophy are a neurodegeneration marker, and they correlate with cognitive deficits and disease progress (24). However, a consensus has not been reached on which specific gait parameters are related to brain atrophy. Furthermore, it is still unclear if DTC in gait variables, including trunk movement, are related to MRI-based markers.

The purpose of this study was to investigate the relationships between brain atrophy and spatiotemporal gait parameters during normal and dual-task walking in older adults. We hypothesized that DTC in spatiotemporal gait parameters in older adults are related to brain atrophy described by MRI-based markers. To acquire quantitative gait variables including variables describing trunk movement and for a variety of conditions, we used a triaxial accelerometer that minimizes restrictions of walking movements (25). Brain atrophy was quantitatively and automatically calculated using a voxel-based analysis system from MRI (26,27).

**METHODS**

**Participants**

One hundred thirty-five people were recruited from our volunteer database, which included older adults aged 65 and older. The inclusion criteria required that participants were living independently in the community and had adequate speech, hearing, and visual acuity to participate in the examinations. Exclusion criteria included having a history of major psychiatric illness, serious neurological or musculoskeletal diagnoses, or depression [Geriatric Depression Scale score ≥ 10 (28)]. Each participant underwent gait experiments and assessments including a face-to-face interview with a clinical nurse, a cognitive assessment by a speech therapist, physical performance tests, and MRI scanning. One hundred ten people met the criteria and participated in this study. The following data were recorded: age, sex, body mass index, and educational history. To assess functional capacity, we used the Tokyo Metropolitan Institute of Gerontology Index of Competence (29) questionnaire (0–13 points). This questionnaire consists of three subscales and each item has 1 point: instrumental self-maintenance (five items), intellectual activity (four items), and social role (four items). General physical function was examined using grip strength and the timed up and go test (30). Grip strength was measured twice while standing, and the higher value was used. The timed up and go test is a mobility test, and participants were asked to walk 3 m, then turn around and walk 3 m, all at their self-selected normal speed in a well-lit environment.

Neuropsychological function was evaluated using the Mini-Mental State Examination (31). The ethics committee of the National Center for Geriatrics and Gerontology approved this study. All participants provided written, informed consent.

**Gait Analysis**

Participants were checked to make sure they were wearing shoes of an appropriate size before each experiment. Then, subjects were instructed to walk on an 11-m smooth, horizontal walkway, with a 2-m space at both ends of the walkway for acceleration and deceleration. Two gait experiments were performed in order: (a) normal walking at the participant’s preferred speed and (b) dual-task walking: walking while counting backward in double digits with a randomly chosen starting number between 50 and 99. The mid 5-m walking time was measured, and gait speed was expressed in meters per second. A triaxial accelerometer (MVP-RF8, acceleration range: ±60 m/sec^2, size: 45 mm width, 45 mm depth, 18.5 mm height, weight: 60 g, sampling rate: 200 Hz; MicroStone, Nagano, Japan) was attached to the L3 spinous process using a Velcro™ belt. The accuracy of data acquisition had been confirmed in a previous study using the same type of sensor (32). Before measurements, the accelerometer was calibrated statically against gravity. After analogue to digital transformation (10-bit resolution), signals were immediately transferred to a laptop PC (Let’s Note CF-W5, Panasonic, Osaka, Japan) via a Bluetooth Personal Area Network. The working range of the accelerometer to the PC was approximately 50 m. Signal processing was performed using commercially available software (MATLAB, Release 2008b, The MathWorks Japan, Tokyo, Japan). The person who processed the acceleration data was blinded to any other results. Before analysis, all acceleration data were low-pass filtered (dual pass zero lag Butterworth filtered) with a cutoff frequency of 20 Hz. Stride time was determined by a validated method reported as the interval from an initial contact event to the next ipsilateral event (33). The mean stride time was calculated from five consecutive stride times. The average stride length was determined by multiplying gait speed by mean stride duration. The harmonic ratio (HR) was used to evaluate the smoothness and stability of trunk movement during gait (3,4,34). Higher HR values indicate greater stability during walking. HR was computed using a digital Fourier transform separately in each direction (vertical: VT direction, mediolateral direction, and anteroposterior direction). The procedure for calculating HR has been reported elsewhere (3,4,34).

**Brain MRI**

MRI was performed on a 1.5-T system (Magnetom Vision, Siemens, Germany). Three-dimensional volumetric acquisition of a T1-weighted gradient echo sequence was used to produce a gapless series of thin sagittal sections using a magnetization preparation rapid-acquisition gradient echo.
sequence (repetition time, 1700 ms; echo time, 4.0 ms; flip angle 15°, acquisition matrix 256 × 256, 1.3 mm slice thickness). The voxel-based specific regional analysis system in this study has been validated (26,27). This system was reformatted to produce gapless 2-mm thin-slice transaxial images, and the first anatomical standardization used affine transformation. The normalized MRI images were then segmented into gray matter, white matter, cerebrospinal fluid, and other components using a modified version of the clustering algorithm, the maximum likelihood “mixture model” algorithm. The segmentation procedure involved a calculation for each voxel using a Bayesian probability of belonging to each tissue class based on a priori MRI information with a nonuniformity correction. The segmented gray matter images were then subjected to an affine and nonlinear anatomical standardization using an a priori gray matter template. The anatomically standardized gray matter images were smoothed with an isotropic Gaussian kernel 12-mm full-width at half-maximum to exploit the partial volume effects, and a spectrum of gray matter intensities was created. We compared the gray matter image of each patient with the mean and standard deviation of gray matter images of healthy volunteers using voxel-by-voxel mean and standard deviation of gray matter images of the healthy volunteers using voxel-by-voxel mean and standard deviation of gray matter images of healthy volunteers using voxel-by-voxel Z score analysis. In the final step, the Z score was calculated according to the following equation:

\[ Z \text{ score} = \frac{[\text{control mean} - \text{individual value}]}{\text{control SD}} \]

The region of brain atrophy was defined as voxels with a Z score greater than 2. The brain atrophy index was defined as the proportion of the number of voxels defined atrophic relative to the total number of voxels of the entire brain.

Statistical Analysis

All analyses were performed using commercially available software (JMP8.0J for Windows, SAS Institute Japan, Tokyo, Japan). The data were normally distributed for all spatiotemporal gait parameters under both normal walking and dual-task walking conditions. Gait parameters were compared between normal walking and dual-task walking using a repeated measures analysis of variance. To assess the association between DTC in gait parameters and brain atrophy, we first confirmed the interaction of the factors brain atrophy (continuous measure) and walking condition (normal walking vs dual-task walking) for each gait parameter using a repeated multivariate analysis of covariance adjusted for covariates (covariates: age, sex, and Mini-Mental State Examination score). Covariates for the interaction were then confirmed using an analysis of variance comparing tertiles of brain atrophy. A linear regression model adjusted for gait speed was used to detect a significant association between brain atrophy and DTC in those gait parameters with a significant interaction between brain atrophy and walking condition. Independent variables included subject characteristics and DTC in gait parameters between walking conditions and were presented as percentage of changes (dual-task walking − normal walking)/normal walking × 100). Statistical significance was set a priori at \( p < .05 \).

Results

The 110 subjects (50% women) were aged between 65 and 94 years with a mean body mass index of 23.1 kg/m^2. The demographic data, general physical performance, functional capacity, and brain atrophy for all subjects are summarized in Table 1. The spatiotemporal gait parameters under normal walking and dual-task walking conditions and a comparison between conditions are presented in Table 2. Gait speed was significantly lower for the dual-task walking compared with the normal walking condition even when adjusted for sex (\( p = .029 \)). Stride length and cadence were lower for dual-task walking condition compared with the normal walking condition even when adjusted for sex and gait speed (stride length: \( p < .001 \), cadence: \( p < .001 \)). The HR of trunk movement in all directions was significantly lower for the dual-task walking condition compared with the normal walking condition even when adjusted for sex and gait speed (VT direction: \( p < .001 \), mediolateral direction: \( p = .002 \), anteroposterior direction: \( p < .001 \)). The repeated multivariate analysis of covariance revealed a significant interaction between walking condition (normal walking vs dual-task walking) and brain atrophy only for HR in VT direction (walking condition × brain atrophy: \( F = 4.334 \), \( p = .040 \)). Linear regression analysis revealed that brain atrophy is independently related to DTC in HR in VT direction (\( \beta = .231 \), \( p = .024 \); Table 3).

Discussion

This study revealed that decreased trunk stability during dual-task walking is significantly associated with brain atrophy in older adults. This association was independent of other variables in a regression model. In addition, dual-task walking resulted in a change of spatiotemporal gait parameters compared with normal walking, even when adjusted for sex and gait speed. The deterioration in HR during dual-task walking was calculated using a specific voxel-based regional analysis system for MRI data.

Table 1. Subject Characteristics and Percentage of Brain Atrophy

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>M ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>75.4 ± 7.1</td>
</tr>
<tr>
<td>Sex, women subjects (%)</td>
<td>55 (50)</td>
</tr>
<tr>
<td>Body mass index (kg/m^2)</td>
<td>23.1 ± 3.3</td>
</tr>
<tr>
<td>Educational history (y)</td>
<td>10.7 ± 2.6</td>
</tr>
<tr>
<td>Mini-Mental State Examination (total score)</td>
<td>26.4 ± 2.5</td>
</tr>
<tr>
<td>Grip strength (kg)</td>
<td>23.5 ± 7.5</td>
</tr>
<tr>
<td>Timed up and go test (seconds)</td>
<td>9.2 ± 2.3</td>
</tr>
<tr>
<td>Geriatric Depression Scale (total score)</td>
<td>3.7 ± 3.0</td>
</tr>
<tr>
<td>Tokyo Metropolitan Institute of Gerontology</td>
<td>12.2 ± 1.1</td>
</tr>
<tr>
<td>Index of Competence (total score)</td>
<td>10.7 ± 4.2</td>
</tr>
<tr>
<td>Brain atrophy (%)</td>
<td>7.6 ± 4.2</td>
</tr>
</tbody>
</table>

 Notes: Values are mean ± SD and numbers (proportion) for sex. Brain atrophy was calculated using a specific voxel-based regional analysis system for MRI data.
Dual tasking decreases HR as indicated by decreased smooth-
teriors observed in our study suggest that dual tasking influences
irregular surface) (4). The DTC in spatiotemporal gait param-
for walking with additional challenges (eg, walking on an
adaptation because similar changes in HR have been reported
among gait variables, type of tasks, or task difficulty (10,12).
Our results were consistent with reported dual-task changes for spatiotem-
poral gait measures, although the magnitude of changes varied
among gait variables, type of tasks, or task difficulty (10,12).
Dual tasking decreases HR as indicated by decreased smooth-
ness of trunk movement and increased trunk instability in all
directions. Furthermore, decreased HR may be caused by an
fact that locomotion requires high-order cognitive processing
such as executive function (5,6,7). Dual tasking generally
affects spatiotemporal gait parameters including lower ex-
tension of trunk movement and increased trunk instability in all
directions. Additionally, dual-task
were observed in all three directions. However, the association
between brain atrophy and DTC in HR was only present in VT
direction.

Both the motor system and the cognitive system act
reciprocally to ensure successful locomotion. To investigate
this interaction, many experiments have been conducted using
the dual-task method (10,11,12). DTC in gait parameters
among older adults as a result of cognitive motor interference
reflect an adaptation to a more challenging conditions and the
fact that locomotion requires high-order cognitive processing
such as executive function (5,6,7). Dual tasking generally
affects spatiotemporal gait parameters including lower extre-
mitry (10,12) and trunk movement (7,13,14,15). Our results
were consistent with reported dual-task changes for spatiotem-
poral gait measures, although the magnitude of changes varied
among gait variables, type of tasks, or task difficulty (10,12).
Dual tasking decreases HR as indicated by decreased smooth-
ness of trunk movement and increased trunk instability in all
directions. Furthermore, decreased HR may be caused by an
adaptation because similar changes in HR have been reported
for walking with additional challenges (eg, walking on an
irregular surface) (4). The DTC in spatiotemporal gait param-
eters observed in our study suggest that dual tasking influences
the control of both lower extremity and trunk movement.

MRI-based measures of brain atrophy are valid parameters
because macrostructural brain abnormalities inevitably lead
to neurodegeneration, neuropsychological deficits, tangle
deposition, and microstructural loss (24). The macrostructural
brain abnormalities associated with gait are hyperintensities
of the white matter (19,20,21) and atrophy of the gray matter
(21,22,23). The brain volume in the sensorimotor and fron-
toparietal regions including the prefrontal lobes is associated
with step time and double support time during normal gait
(22), and the differences between intracranial and brain
volume were independently related to slower gait speed in
women after adjusting for covariates (21). While one study
reported that hippocampal volume is related to gait speed
(23), results of another study suggest that gait performance
among older adults is not necessarily related to atrophy in
the memory domain including the hippocampus (22). The
latter study also reported a weak association between gait
measures and brain volume in the cerebellum or basal ganglia
structures—regions that play key roles in the control of
balance. A consensus has not been reached on the relationship
between quantitative MRI-based measures of brain atrophy
and gait variables. The results of our study indicate that DTC
in trunk movement is significantly related to brain atrophy
measured using the voxel-by-voxel method, which has been
validated in other studies (26,27). Rosano and colleagues (22)
suggested that gait variables under several conditions, includ-
ing difficult conditions, should be investigated to clarify the
task-specific network in the brain. Our initial results indicate
that DTC in trunk movement might be associated with brain
atrophy.

The control of trunk movement contributes to successful
locomotion and is under continuous active neural control (1).
The neural network may prioritize trunk stability to increase
head stability during walking (35). Additionally, dual-task
walking requires successful allocation of attention to both
walking and the other task, which relies on executive function.
In fact, dual-task decrements of gait measures are related to
cognitive performance such as executive function (5,6,7), and
both mobility and cognitive function are enhanced by dual-task
intervention training as shown by results of randomized clin-
ical trials (16,17). Because dual-task walking requires the

Table 2. Paired Comparison of Spatiotemporal Gait Parameters for Normal Walking and Dual-Task Walking

<table>
<thead>
<tr>
<th>Variables</th>
<th>Normal Walking (M ± SD)</th>
<th>Dual-Task Walking (M ± SD)</th>
<th>Mean Difference (95% CI)</th>
<th>p Value</th>
<th>Adjusted p Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gait speed (m/s)</td>
<td>1.10 ± 0.26</td>
<td>1.04 ± 0.31</td>
<td>−0.05 (−0.10, −0.01)</td>
<td>.022</td>
<td>.029†</td>
</tr>
<tr>
<td>Stride length (m)</td>
<td>1.13 ± 0.21</td>
<td>1.19 ± 0.41</td>
<td>0.06 (−0.01, 0.13)</td>
<td>.103</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Cadence (steps/min)</td>
<td>115.8 ± 12.3</td>
<td>107.6 ± 17.8</td>
<td>−8.0 (−12.21, −3.80)</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Harmonic ratio</td>
<td>Vertical</td>
<td>2.84 ± 0.86</td>
<td>−0.38 (−0.64, −0.12)</td>
<td>.005</td>
<td>&lt;.001</td>
</tr>
<tr>
<td></td>
<td>Mediolateral</td>
<td>2.12 ± 0.65</td>
<td>−0.19 (−0.36, −0.01)</td>
<td>.036</td>
<td>.002</td>
</tr>
<tr>
<td></td>
<td>Anteroposterior</td>
<td>3.13 ± 1.04</td>
<td>−0.53 (−0.79, −0.25)</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

Notes: CI = confidence interval.
*Adjusted for sex and gait speed.
†Adjusted only for sex.

Table 3. A Linear Regression Model for Brain Atrophy

<table>
<thead>
<tr>
<th>Variables</th>
<th>β (SE)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>.352 (.004)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Gender</td>
<td>.462 (.034)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Body mass index</td>
<td>.240 (.007)</td>
<td>.010</td>
</tr>
<tr>
<td>Educational history</td>
<td>−.028 (.010)</td>
<td>.779</td>
</tr>
<tr>
<td>Mini-Mental State</td>
<td>−.143 (.011)</td>
<td>.164</td>
</tr>
<tr>
<td>Examination score</td>
<td>.072 (.023)</td>
<td>.469</td>
</tr>
<tr>
<td>Grip strength</td>
<td>−.082 (.005)</td>
<td>.540</td>
</tr>
<tr>
<td>Tokyo Metropolitan Institute of Gerontology Index of Competence</td>
<td>.249 (.008)</td>
<td>.016</td>
</tr>
<tr>
<td>Geriatric Depression Scale</td>
<td>.231 (.062)</td>
<td>.024</td>
</tr>
<tr>
<td>Dual-task–related changes of HR in VT direction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R² = .362

Notes: HR = harmonic ratio; VT = vertical. A linear regression model was used to examine the association between dual-task–related changes of the gait parameter and brain atrophy, adjusted for gait speed.
simultaneous control of walking and an additional task, the demand on neural resources for postural adjustments during walking may be greater for dual-task walking compared with normal walking. The analysis of HR during dual-task walking revealed an association between DTC in HR and brain atrophy; however, there was no relationship between DTC in other gait variables and brain atrophy. These results suggest that HR during dual-task walking may be a biomechanical marker for identifying a decline in brain volume.

Although dual-task walking decreased HR for trunk movement in all directions, an association between brain atrophy and DTC in HR was only observed in VT direction. These observations agree with results of other studies that HR data for lower trunk acceleration may represent different phenomena depended on the direction (2,36). Menz and colleagues (2) reported that directional specificity in HR in older adults was greater while walking under more challenging conditions. Results of their study suggested that the HR value of the lower trunk in VT direction had the ability to detect instability under challenging conditions. In another study, Brach and colleagues (3) suggested that HR in anteroposterior direction represents age-related changes that are not even affected by gait speed. The directional specificity of HR was not fully clarified, and further evidence for this specificity is required. Nevertheless, the results of our study indicate that brain atrophy is more likely to be related to trunk instability in the VT direction than in the anteroposterior and mediolateral directions induced by dual-task walking.

One limitation of this study is the relatively small sample size. Additionally, some physical dimensions, such as fitness level (37) and static postural instability (38), may have acted as confounding factors but were not included in this study. Furthermore, the effects of executive function and attention as confounding factors could influence dual-task gait performance (6,12) and should be considered to generalize these results. Moreover, the type and/or difficulty of dual-task walking in this study could have affected the results. Hence, dual-task walking using other types of cognitive tasks (eg, verbal fluency) should further be investigated. Finally, in this study, we measured atrophy of the entire brain. It is likely that regional atrophy assessed by MRI and other macrostructural measures (eg, white matter lesions) will provide a better insight into the mechanistic relationship between brain atrophy and gait function.

**Conclusion**

Brain atrophy correlated with a decline in the control of trunk movement during dual-task walking. This result indicates that dual-task walking induces trunk instability because additional cognitive resources are required compared with that during normal walking. Further studies are needed to clarify the effects of regional structural brain loss on the control of trunk movement and limb control during walking.

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