Gait asymmetry in patients with Parkinson’s disease and elderly fallers: when does the bilateral coordination of gait require attention?

Galit Yogev · Meir Plotnik · Chava Peretz · Nir Giladi · Jeffrey M. Hausdorff

Received: 26 June 2006 / Accepted: 10 August 2006 © Springer-Verlag 2006

Abstract While it is known that certain pathologies may impact on left–right symmetry of gait, little is known about the mechanisms that contribute to gait symmetry or how high in the hierarchy of the control of gait symmetry is regulated in humans. To assess the contribution of cognitive function to gait symmetry, we measured gait asymmetry (GA) in three subject groups, patients with Parkinson’s disease (PD, n = 21), idiopathic elderly fallers (n = 15), and healthy elderly controls (n = 11). All subjects walked under two walking conditions: usual walking and dual tasking (cognitive loading) condition. For each subject, the swing time (SW) was calculated and averaged across strides for the left and right feet (SWL and SWR). GA was defined as: 100 \times |\ln(SWR/SWL)|. For both the PD patients and the elderly fallers GA values were significantly higher during the usual walking condition, as compared with the control group (P < 0.01). In addition, for both the PD patients and the elderly fallers, GA significantly increased when they walked and performed a dual task, compared with the usual walking condition (P < 0.003). In contrast, dual tasking did not affect the GA of the healthy controls (P = 0.518). GA was associated with gait speed and gait variability, but no correlations were found between GA and the asymmetry of the classic PD motor symptoms. Thus, the results suggest that the ability to generate a steady, rhythmic walk with a bilaterally coordinated gait does not rely heavily on mental attention and cognitive resources in healthy older adults. In contrast, however, when gait becomes impaired and less automatic, GA apparently relies on cognitive input and attention.

Keywords Asymmetry · Bilateral coordination · Gait · Cognitive function · Dual tasking

Introduction

The focus of this paper is on gait asymmetry (GA), specifically, the bilateral lower extremity coordination of the timing of swing durations during gait. Traumatic unilateral pathology, such as that which may occur as a result of a stroke (Wall and Turnbull 1986; Lin et al. 2006), often results in a markedly asymmetric gait. Under healthy, physiologic conditions, however, gait is generally symmetric, i.e., the left and right lower
extremities behave similarly. The mechanisms responsible for this left–right coordination are not fully understood. The primary objective of the present study was to more fully identify some of the factors that contribute to gait (a)symmetry.

In a recent review, Sadeghi et al. describe evidence of subtle GA in healthy adults, both in terms of spatial-temporal parameters (e.g., stride length) and kinetic parameters (e.g., asymmetries in EMG amplitude profiles for the soleus and rectus femoris muscles, and asymmetries of anterior-posterior and medio-lateral components of ground reaction forces) (Sadeghi et al. 2000). As noted, in the presence of pathology, asymmetry may become even more exaggerated. For example, GA has been reported in patients with Parkinson’s disease (PD) (Plotnik et al. 2005), in patients recovering from cerebrovascular accidents (Wall and Turnbull 1986) and in amputees (Skinner and Effeney 1985). In certain cases, the source of GA is clear (Lin et al. 2006). Often, however, the factors that produce an asymmetric gait are less obvious. Only a handful of studies have quantified GA in PD (Miller et al. 1996; Plotnik et al. 2005; Baltadjieva et al. 2006). GA was observed even in patients in the early stages of the disease (Baltadjieva et al. 2006), but the degree of GA was not associated with the level of asymmetry in the motor symptoms of the disease (e.g., rigidity, tremor) (Plotnik et al. 2005). In general, little is known about the mechanisms that contribute to GA or how high in the hierarchy of the control of gait is asymmetry regulated in man.

Investigations of the neural basis of left–right gait coordination are primarily based on findings from animal models. Such studies indicate that locomotor rhythmic activity relies on the auto-activity of localized networks of neurons or central pattern generators (CPGs) within an animal’s nervous system (Marder and Calabrese 1996). In animals, the CPGs’ reside as half-center modules in the cervical and lumbar regions of the spinal cord, each generating basic motor output patterns responsible for rhythmic contractions of antagonistic flexor–extensor groups of muscles in the corresponding forelimb or hindlimb (Grillner 1981). Further, pathways mediating left–right alternations exist primarily in the ventral commissural fibers, most likely distributed along several spinal segments (Kjaerulff and Kiehn 1996). There is evidence that interlimb coordination during human locomotion is organized in a similar way to that in quadrupeds (Dietz 2002). Recent investigations using split-belt treadmills to study stepping in infants support the idea that there are autonomous pattern generators for the left and right legs in humans (Yang et al. 2005). Further, healthy young adults are able to move their left and right legs at very different speeds (by as much as a 1.5 m/s difference), suggesting that autonomous pattern generators exist in adults as well (Jensen et al. 1998; Dietz et al. 1994). Thus, extrapolating from these reports, one could suggest that lower-level spinal centers regulate left–right coordination.

Recent studies draw attention to the association between gait disturbances and cognitive function (O’Shea et al. 2002; Woollacott and Shumway-Cook 2002; Yoge et al. 2005; Springer et al. 2006; Verghese et al. 2002; Bloem et al. 2001). This association is commonly studied using dual tasking paradigms, i.e., a subject walks while simultaneously performing a secondary, dual task. If a gait property is automated and does not require cognitive function, one would anticipate that performance of a second task would not alter that aspect of gait. Alternatively, if that property depends on cognitive function, the capacity sharing theory would suggest that as cognitive resources are taxed during dual tasking, performance of one or both of the tasks will deteriorate (Passler 1994; Schmidt and Lee 1999). Consistent with these ideas, previous studies demonstrated that dual tasking affects certain aspects of gait in specific populations in particular ways. Healthy young adults reduce their gait speed when they are asked to walk and perform a second task simultaneously (Springer et al. 2006), while other aspects of gait are generally not affected by dual tasking (Woollacott and Shumway-Cook 2002; Springer et al. 2006). Healthy older adults reduce their gait speed as well as the time spent in swing time, increasing support time, while gait variability (i.e., stability of gait as measured by the stride-to-stride fluctuations in the stride time) is not altered, even when the dual task becomes extremely challenging (O’Shea et al. 2002; Springer et al. 2006). In contrast, dual tasking adversely affects multiple aspects of gait in patients with PD and in older adult idiopathic fallers (i.e., those elderly who fall without any clear reason) (Bond and Morris 2000; Camicio et al. 1998; O’Shea et al. 2002; Yoge et al. 2005; Springer et al. 2006; Bloem et al. 2001). Patients with PD and elderly fallers walk more slowly when asked to perform a cognitive task simultaneously, with a reduced swing time and with an increased stride variability (Bond and Morris 2000; O’Shea et al. 2002; Springer et al. 2006; Yoge et al. 2005). The frequency of freezing of gait episodes also increases when patients with PD are asked to walk and dual task (Camicio et al. 1998). Thus, in these two populations as in others as well (e.g., patients with Alzheimer’s disease), dual tasking not only reduces gait speed, it
also exacerbates instability and other markers of fall risk (Bloem et al. 2003; Sheridan et al. 2003; Lundin-Olsson et al. 1997). Conversely, when patients with PD attend to and focus on their gait, many features improve (Morris et al. 1996; Van Wegen et al. 2006), strengthening the idea that these patients rely on cognitive input.

Given what is known about the interaction between gait and cognitive function, the question arises whether gait symmetry depends in part on cognitive function and if so, is it sensitive to cognitive loading (i.e., dual tasking). Since many aspects of gait and balance are influenced by dual tasking (O’Shea et al. 2002; Woollacott and Shumway-Cook 2002; Yogev et al. 2005), one could suggest that the left–right regulation of asymmetry also utilizes cognitive resources and hence will be altered during dual tasking conditions. On the other hand, the animal studies suggest that the generation of a symmetric gait may be a relatively automated, lower-level task and thus should not be sensitive to cognitive loading and dual tasking. To our knowledge, only one study has begun to examine this question. Yang et al. found that dual tasking did not affect the temporal asymmetry of gait in healthy control subjects, while asymmetry became larger during dual tasking in patients who had suffered a stroke (Yang et al. 2006). This suggests that the possibility that healthy gait symmetry does not utilize significant cognitive resources, but when gait becomes less automatic, as may occur during certain pathological states, left–right symmetry coordination may require additional cognitive input and become sensitive to cognitive loading.

To further address this question and examine left–right asymmetry in man, we evaluated the temporal GA of three groups of subjects: healthy older adults, elderly fallers, and patients with PD, both during usual walking and during dual tasking. These three groups have diverse characteristics that allow for the study of asymmetry in subjects with a range of walking properties. For example, patients with PD walk with reduced automaticity of certain aspects of gait and asymmetric clinical symptoms. Idiopathic fallers have an increased fall risk without known asymmetry, and the healthy control group provides a basis for comparison. This combination enables us to obtain a more complete understanding of asymmetry, the factors that influence it, and its potential clinical utility. Based on the initial report in patients with a history of stroke (Yang et al. 2006), we hypothesized that for healthy subjects, when gait is relatively automatic, gait symmetry will utilize lower-level processes that do not tax cognitive function and, therefore, that asymmetry would not be affected by dual tasking. In addition, we hypothesized that asymmetry would be larger in the patients with PD, compared with controls, under usual single task walking conditions and that asymmetry would be similar in elderly fallers and controls under that condition. Finally, given the alterations in automaticity and increased stride variability in patients with PD and in elderly fallers when they are exposed to secondary tasks during walking, we hypothesized that in these two patient groups, dual tasking would increase asymmetry. In secondary analyses, we explored the relationship between GA and other markers of disability and instability including parkinsonian motor symptoms, gait speed, stride length, and gait variability in order to gain additional insight into this relatively poorly studied feature of human locomotion.

Methods

This study is a new analysis of data that was partially described previously (Springer et al. 2006; Yogev et al. 2005). In the earlier reports, asymmetry was not determined and the analyses were based on the evaluation of just one foot. Because of our interest in asymmetry in the present investigation, we used only those previously obtained datasets where data was available from both the left and right feet. Thus, the population reported here is a subset of the earlier reports. Here we briefly describe the study participants and data collection procedures. Further details are included in the earlier reports (Springer et al. 2006; Yogev et al. 2005).

Subjects

We studied 21 patients with idiopathic PD, as defined by the UK Brain Bank criteria (Gelb et al. 1999), 15 idiopathic elderly fallers, and 11 healthy elderly controls. Patients with PD were recruited from the outpatient clinic of the Movement Disorders Unit at the Tel-Aviv Sourasky Medical Center. The elderly fallers and the controls were recruited from several sources in the community: patients’ spouses, local senior centers, and volunteers from the community. It was a convenient sample.

Elderly subjects (PD patients, fallers, and healthy controls) were invited to participate if they were able to ambulate independently, they did not have dementia [as determined by DSM IV criteria and scores > 24 on the Mini Mental State Exam (MMSE) (Folstein et al. 1975)], and they were between 60 and
85 years of age. Subjects were excluded if they had clinically significant musculo-skeletal disease, cardiovascular disease, respiratory disease, cerebrovascular, or other neurological disease (for example, subjects with a history of a stroke or head injury), major depression, or uncorrected visual disturbances. In addition, PD patients were included if their disease stage was 2–3 on the Hoehn and Yahr scale (Hoehn and Yahr 1967), they were taking anti-parkinsonian medications, and they did not experience motor response fluctuations. The older adults were classified as fallers if they reported one or more falls, of unknown origin, in the previous 6 months. All fallers reported two or more falls in the previous year and thus can be considered multiple or recurrent fallers. The Human Studies Committee of Tel-Aviv Sourasky Medical Center approved the study. All subjects gave their written informed consent according to the declaration of Helsinki, prior to entering the study.

Procedures

After providing informed consent, the subjects underwent several assessments. The study population was characterized with respect to age, gender, and the MMSE (Folstein et al. 1975) (a gross measure of cognitive function widely used to screen for dementia). Subjects were also asked about their history of falls in the past 6 months. The motor portion of the Unified Parkinson's Disease Rating Scale (UPDRS) was used to quantify disease severity and extra-pyramidal signs (Fahn et al. 1987). All participants also completed Mindstreams® (NeuroTrax Corp., New York, NY, USA), a computerized cognitive test battery designed to evaluate multiple cognitive domains (Dwolatzky et al. 2003; Springer et al. 2006; Yogev et al. 2005). Briefly, the battery includes classic neuropsychological tests of attention and executive function (e.g., the Stroop test, the Go-No-Go Response Inhibition test) and uses these tests to determine a global score (“index”) of attention and executive function. Previous work has shown that such measures are related to dual tasking measures of gait variability (Springer et al. 2006; Yogev et al. 2005) and that they respond as expected to cognitive-enhancing pharmacologic therapy (Auriel et al. 2006).

Walking protocol and dual tasking

Gait was examined under two conditions: (1) baseline (usual walking with no dual task), and (2) while the subject was asked to perform an arithmetic task. During the baseline condition, subjects walked at a comfortable pace without any secondary task in a well-lit, obstacle-free, 25-m long, 2-m wide corridor. During the arithmetic task, subjects walked while performing serial 7 subtractions out loud, starting from 500. These walking trials were carried out after a practice trial in which subjects were familiarized with the surroundings and the procedures. A summary score of performance was determined as the ratio of the number of subtraction errors to the number of subtractions. Subjects were instructed to walk at their normal pace on level ground for 2 min under each condition (usual walking and dual tasking condition). The instructions for the dual tasking condition were to walk at a comfortable pace and to perform the secondary task. No instruction for priority of one of the tasks (walking vs. arithmetic task) was given.

Gait assessment

A previously described computerized force-sensitive system was used to quantify gait cycle timing, specifically the swing time and the stride-to-stride variability of swing time (Yogev et al. 2005; Bazner et al. 2000; Frenkel-Toledo et al. 2005). The system measures the forces underneath the foot as a function of time. The system consists of a pair of shoes and a recording unit. Each shoe contains eight load sensors that cover the surface of the sole and measure the vertical forces under the foot. The recording unit (19 cm × 14 cm × 4.5 cm; 1.5 kg) is carried on the waist. Plantar pressures under each foot are recorded at a rate of 100 Hz. Measurements are stored in a memory card during the walk, and, after the walk, they are transferred to a personal computer for further analysis. The focus of this study was on the assessment of asymmetry and bilateral coordination of gait; thus, gait parameters were evaluated for each foot separately. The following parameters were determined:

- **Left swing time**: the time the left foot was in the air, averaged across all strides.
- **Right swing time**: the time the right foot was in the air, averaged across all strides.
- **Left swing variability**: the coefficient of variation (CV; CV = 100 × standard deviation/mean) of the left swing time.
- **Right swing variability**: CV of the right swing time.
- **Short and long swing time (SSWT and LSWT, respectively)**: For each subject, we determined which foot
had the shorter and longer mean swing times by comparing the average swing durations (measured in second) of each foot.

Short and Long swing time CV (SSWCV and LSWCV, respectively): CV values of SSWT and LSWT, respectively.

Gait asymmetry: \[ GA = 100 \times \ln \left( \frac{\text{SSWT}}{\text{LSWT}} \right) \].

This definition is similar to that used by Yang et al. (2006) and identical to a previous one (Plotnik et al. 2005), except for the scaling factor of 100. With this definition, values of 0.0 reflect perfect symmetry and higher values reflect greater degrees of asymmetry. Because left and right swing times are essentially independent bio-mechanically (think about the person with a hemi-paretic gait who drags one leg while the other is relatively normal), the swing time ratio provides a measure of temporal left–right asymmetry. In practice, we have seen values ranging from 0 to 57. (One might also suggest an alternative measure of asymmetry: Gait CV asymmetry = 100 \times \ln \left( \frac{\text{SSWCV}}{\text{LSWCV}} \right).) This measure, which reflects potential left–right differences in the stride-to-stride variability of each leg, was not significantly different in the control and patient groups and was not significantly affected by dual tasking in any of the groups. Given that previous work used the above-defined measure of GA and for the sake of brevity, only the single measure GA based on average swing times is reported.) Average gait speed was determined using a stop watch by measuring the average time the subject walked the middle 8 m of the 25 meter walk during the 2 min of testing. Average stride length was determined from gait speed and stride time.

UPDRS asymmetry: For each side of the body, we calculated the sum of scores of UPDRS items 20–26 (these items refer to rest tremor, action or postural tremor, rigidity, finger taps, hand movements, rapid alternating movements of the hands and leg agility, respectively). UPDRS asymmetry was defined as the ratio: \[(\text{higher sum}–\text{lower sum})/(\text{higher sum} + \text{lower sum})\].

Statistical analysis

Descriptive statistics are reported as mean ± SD. In order to estimate the effect of the serial 7 subtraction (dual tasking) on GA, we applied mixed effect models for repeated measures to evaluate within group and between group differences. We assumed variance heterogeneity (unequal variance of PD patients, idiopathic fallers and controls). The dependent variable was GA (a continuous one) and the independent variables were categorical: the group (PD patients, elderly fallers, and controls) and the secondary task (baseline walking, walking while performing serial 7 subtraction), and the group × secondary task condition interaction term. The fixed factors in these models were group and the secondary task while the subject was the random factor. In the model, for the secondary task, the “none” category was considered as the reference category, inherent in the modeling procedure. Thus, each subject’s usual walking serves as his/her reference values. Mixed effect models were evaluated with and without the inclusion of age as a co-variate. Because inclusion of age did not affect the results, we report the results based on the unadjusted models. \( P \)-values reported are based on a two-sided comparison. A \( P \)-value ≤ 0.05 was considered statistically significant. All statistical analyses were performed using SAS 9.1 (Proc Mixed).

Results

Subject characteristics and baseline measures

Table 1 summarizes the demographic and clinical characteristics of the study population. PD patients and

<table>
<thead>
<tr>
<th>Table 1  Subject characteristics</th>
<th>Controls ((n = 11))</th>
<th>PD patients ((n = 21))</th>
<th>Fallers ((n = 15))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>67.5 ± 3.5</td>
<td>71.9 ± 7.3 (0.029)</td>
<td>76.3 ± 4.9 (&lt;0.001)</td>
</tr>
<tr>
<td>Gait speed (m/s)</td>
<td>1.36 ± 0.16</td>
<td>1.00 ± 0.25 (&lt;0.001)</td>
<td>0.97 ± 0.25 (&lt;0.001)</td>
</tr>
<tr>
<td>Swing time (s)</td>
<td>0.40 ± 0.04</td>
<td>0.38 ± 0.04 (0.14)</td>
<td>0.40 ± 0.03 (0.90)</td>
</tr>
<tr>
<td>Swing time variability (%)</td>
<td>2.2 ± 0.5</td>
<td>3.6 ± 1.3 (0.002)</td>
<td>3.6 ± 1.3 (0.002)</td>
</tr>
<tr>
<td>Part 3: motor of UPDRS</td>
<td>0.2 ± 0.6</td>
<td>20.4 ± 7.9 (&lt;0.001)</td>
<td>2.9 ± 1.9 (&lt;0.001)</td>
</tr>
<tr>
<td>MMSE</td>
<td>29.5 ± 0.7</td>
<td>28.3 ± 1.30 (0.010)</td>
<td>28.3 ± 1.4 (0.021)</td>
</tr>
<tr>
<td>Executive function index</td>
<td>107.3 ± 7.6</td>
<td>94.4 ± 8.6 (&lt;0.001)</td>
<td>92.5 ± 9 (&lt;0.001)</td>
</tr>
<tr>
<td>Attention index</td>
<td>101.6 ± 7</td>
<td>96.8 ± 10.6 (0.14)</td>
<td>92.1 ± 11.7 (0.016)</td>
</tr>
</tbody>
</table>

Entries are mean ± SD (\( P \)-value), where the \( P \)-value is based on the comparison with the control subjects. Gait parameters presented for usual walking. Values for swing time and swing time variability are based on “long” swing time (see Sect. “Methods”).

UPDRS Unified Parkinson’s Disease Rating Scale, MMSE Mini Mental State Examination
idiopathic fallers were a few years older than the healthy elderly controls. There tended to be more men among the PD patients (81% of PD were male) than in the control subjects (55%) or in the fallers (47%), however, male–female ratios were not significantly different in the control group and the two patient groups ($P > 0.10$ by Chi-square analysis). Although the MMSE values in these two groups (i.e., PD patients and idiopathic fallers) were significantly lower than the values observed in the controls, the differences were relatively small. PD patients and idiopathic fallers scored significantly lower on the executive function index. The attention index was significantly lower for the idiopathic fallers, as compared with controls.

Scores on the motor portion of the UPDRS were significantly higher, as expected, for the PD patients. For the idiopathic fallers, UPDRS scores were slightly higher than control values. The mean value (2.9) seen in the fallers can be considered as negligible and is not indicative of any pathology. Most of the fallers that had non-zero scores on the UPDRS received points for their performance on items related to balance and gait (items 29–30). Swing time variability was significantly higher for both PD patients and idiopathic fallers, compared with healthy elderly controls ($P = 0.001$ for both groups). The UPDRS asymmetry index for the PD patients was $0.20 \pm 0.15$. Under usual walking conditions, GA was significantly higher in both patient groups compared with the controls (see Table 2).

**Effects of dual tasking on gait asymmetry**

Asymmetry of gait significantly increased during the dual task condition in the PD patients and in the idiopathic fallers, but not in the healthy controls. Figure 1 illustrates this point. Swing times are plotted for a series of strides. For the PD patient and the idiopathic faller, swing time values of one leg become more distinct from the swing time values of the other leg during dual tasking gait, reflecting a higher degree of GA, as compared with baseline walking.

Table 2 and Fig. 2 summarize the effects of dual tasking on GA in all three groups. For the control

![Fig. 1 Swing times of each foot in a control subject, PD patient, and idiopathic faller. The left columns and right columns show swing time and asymmetry during usual walking and during dual tasking. The effect of dual tasking, respectively (i.e., mental loading) is clearly apparent for the PD patient and the idiopathic faller, where right foot values become further separated from the left foot values. Such an effect was not present for the control subject. For the control subject, GA values were 0.3 and 1.0 in the usual walking and the dual task conditions, respectively. The corresponding values were 3.0 and 7.0 for the PD patient and 0.2 and 4.5 for the idiopathic faller](image_url)

<table>
<thead>
<tr>
<th>Table 2 Gait asymmetry during usual walking and during dual tasking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usual walking</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>Healthy controls ($n = 11$)</td>
</tr>
<tr>
<td>PD patients ($n = 21$)</td>
</tr>
<tr>
<td>Fallers ($n = 15$)</td>
</tr>
</tbody>
</table>

Entries are mean ± SE and in parentheses. $P$-values compared with the healthy controls

$^a$ $P$-values based on mixed model analyses unadjusted for age, however, adjustment of age did not alter any of the findings
baseline walking ($P = 0.001$, $0.003$, respectively). Consistent with this, the effect of dual tasking was different among the groups (interaction effect of group $\times$ type of walking, $P = 0.043$). Performance on the secondary task, i.e., serial 7 subtractions, was best in the healthy control ($P < 0.05$ compared with both patient groups) and was similar in the PD patients and fallers ($P = 0.99$).

Correlates of gait asymmetry

Table 3 summarizes the associations between GA, gait speed, stride length, gait variability, and motor symptoms. Not surprisingly, across all subjects, long swing CV was strongly correlated with short swing CV, both in the usual walking and dual tasking conditions (Spearman’s correlation coefficients—$ho = 0.78$ and 0.82, respectively, $P < 0.001$). Hence, correlations are presented only for the long swing CV parameter. During usual walking, GA was most closely related to gait speed, but even in this case, gait speed explained only about 25% of the variance in asymmetry. During dual tasking, GA was most closely associated with swing time variability, but the latter explained less than 20% of the variance in GA. GA was not significantly associated with UPDRS asymmetry scores on the motor part of the UPDRS. Correlations between scores of the motor part of the UPDRS and GA were weak both for baseline walking and dual task walking. There were no significant gender differences in GA in any of the three groups ($P > 0.28$) or if all subjects

### Table 3: Correlations between GA and other features under usual walking and dual tasking conditions

<table>
<thead>
<tr>
<th>Feature</th>
<th>Usual walking</th>
<th>Dual tasking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gait measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gait speed</td>
<td>$-0.50$ (0.001)</td>
<td>$-0.37$ (0.012)</td>
</tr>
<tr>
<td>Stride length</td>
<td>$-0.47$ (0.001)</td>
<td>$-0.36$ (0.013)</td>
</tr>
<tr>
<td>Swing time variability</td>
<td>$0.25$ (0.017)</td>
<td>$0.26$ (0.006)</td>
</tr>
<tr>
<td>Swing time asymmetry</td>
<td>$0.57$ (0.041)</td>
<td>$0.37$ (0.010)</td>
</tr>
<tr>
<td>Swing time variability asymmetry</td>
<td>$0.34$ (0.11)</td>
<td>$0.26$ (0.26)</td>
</tr>
<tr>
<td>Swing time asymmetry</td>
<td>$0.29$ (0.013)</td>
<td>$0.25$ (0.010)</td>
</tr>
<tr>
<td>Swing time variability asymmetry</td>
<td>$0.14$ (0.35)</td>
<td>$0.24$ (0.11)</td>
</tr>
<tr>
<td>Motor UPDRS asymmetry</td>
<td>$-0.40$ (0.086)</td>
<td>$-0.40$ (0.111)</td>
</tr>
<tr>
<td>Executive function</td>
<td>$-0.17$ (0.25)</td>
<td>$-0.17$ (0.25)</td>
</tr>
<tr>
<td>Attention</td>
<td>$-0.24$ (0.11)</td>
<td>$-0.24$ (0.11)</td>
</tr>
</tbody>
</table>

Entries are Spearman’s correlation coefficients ($r$-values). Values for swing time and swing time variability are based on “long” swing time (see Sect. “Methods”). Correlations based on all subjects; similar within group associations were observed. UPDRS asymmetry reported only for PD subjects. During both usual and dual task walking, only modest correlations between GA and other features of gait and clinical characteristics are observed.
were pooled together \((P > 0.18)\). GA during baseline and the dual task condition was not significantly associated with the MMSE or cognitive function indices of executive function or attention \((P > 0.11)\), however, the executive function index was mildly correlated with serial 7 performance \((r = 0.32, P = 0.047)\). Of note, about half of the subjects with PD reported a history of falls in the past 6 months. In the PD group, GA was not correlated with fall frequency, both at baseline and during dual tasking, nor was it different in PD fallers and PD non-fallers \((P > 0.34)\).

### Discussion

This study has several key findings: (1) Confirming clinical studies, we observed increased GA in patients with PD, compared with controls. Interestingly, however, clinical symptoms were not closely associated with the measured asymmetry of bilateral coordination. (2) Somewhat unexpectedly, we found that GA was also increased among elderly idiopathic fallers, compared with controls. (3) As hypothesized, in patients with PD and in idiopathic elderly fallers, but not in healthy elderly adults, gait became more asymmetric during dual tasking. Swing times of one leg become more different than the swing times of the contralateral leg when patients with PD and elderly fallers are asked to walk and perform another cognitively demanding task. This finding extends previous work that has shown that certain aspects of gait may depend on cognitive function and attention (Springer et al. 2006; Woollacott and Shumway-Cook 2002; Yogev et al. 2005; Bloem et al. 2001; Morris et al. 1996; Auriel et al. 2006; Van Wegen et al. 2006; Verghese et al. 2002). Here we demonstrate that even the regulation of asymmetry may rely on cognitive function.

**Gait asymmetry during usual walking**

For both PD patients and idiopathic fallers, we find that GA is increased in comparison with healthy elderly subjects during usual, baseline walking. Recently, we studied GA in more advanced PD patients with motor fluctuations (Plotnik et al. 2005). GA was increased while the patients were “Off” their anti-parkinsonian medications as compared with the “On” state, and GA was higher among PD patients who suffer from freezing of gait episodes as compared with those who were spared from this debilitating phenomenon. Of note, the values observed in the present study in the patients with PD, whose disease had not yet progressed to the point where they had motor response fluctuations, were generally lower than those previously reported in more advanced PD. Taken together, these observations suggest that GA becomes worse during the course of PD.

One may argue that GA in PD is merely a reflection of the asymmetric motor symptoms of PD. This was not the case among the PD patients with motor fluctuations for whom no correlation between GA and asymmetry in the motor signs of PD, as derived from the scores of the UPDRS (Plotnik et al. 2005). Similarly, in the present study, UPDRS asymmetry was not associated with GA (recall Table 3). In other words, asymmetric clinical symptoms such as tremor and rigidity do not fully account for the existence of GA as expressed by the differences in swing times that are generated by each leg.

Only modest correlations between GA and other features of gait and disease were found in both walking conditions (Table 3). Because of the central role of stride length in parkinsonian gait (Morris et al. 1994a, b, 1996), one might have anticipated that the measure of asymmetry would be closely related to stride length. However, this was not the case. Among all subjects, less than 25% of the variance in asymmetry was explained by stride length, both during usual walking and dual tasking. Even among the subjects with PD, only 31% of the variance in asymmetry was explained by stride length during usual walking and this was reduced to 15% during dual walking (data not shown). Similarly, previous work has shown that gait variability plays a significant role in the gait of elderly fallers and patients with PD (Blin et al. 1990; Hausdorff et al. 1998, 2001; Hausdorff 2005; Schaafsma et al. 2003; Springer et al. 2006; Yogev et al. 2005), leading one to speculate that a close association exists between gait variability and asymmetry. A strong association between variability and asymmetry was, however, was not observed (recall Table 3). Based on these findings, one may draw the conclusion that GA may be a relatively independent measure of gait disturbances that reflects distinct pathological processes. In order to substantiate this possibility further, additional controlled studies among healthy as well as gait impaired populations are needed.

**Aggravation of gait asymmetry due to cognitive loading**

The finding that a cognitive challenge heightens GA in patients with PD and idiopathic fallers suggests that the generation of a symmetric gait, like the control of gait rhythmicity, is not quite automatic, at least in certain populations. In healthy older adults,
GA behaves similar to that of a low-level, reflex-like property like that seen in animal models; it is not affected by cognitive loading and apparently does not utilize higher-level cognitive resources. In contrast, among the two patient groups, the left–right coordination of gait appears to demand cognitive (attentional) resources. Cognitive abilities were found to be slightly impaired both in PD patients and in elderly idiopathic fallers (recall Table 1). Based on this and the fact that gait deteriorates when these patients are exposed to cognitive loading, one could suggest that elderly subjects who suffer from motor deficits, cognitive impairments, or both might have difficulties regulating gait rhythm and coordinating symmetric leg movements while walking. Consistent with the results observed in post-stroke patients (Yang et al. 2006), when gait becomes impaired and less automatic, bilateral coordination becomes sensitive to dual tasking.

An alternative explanation which posits that bilateral coordination does not directly utilize cognitive resources should be considered. Given the previously described affects of cognitive loading and dual tasking on postural control and gait (O’Shea et al. 2002; Woollacott and Shumway-Cook 2002; Yogev et al. 2005; Springer et al. 2006), one could argue that dual tasking affects postural control during walking and this in turn modifies the swing times. Indeed, in response to dual tasking, patients with PD and idiopathic fallers walk more slowly and reduce their average swing times (Springer et al. 2006; Yogev et al. 2005). However, this argument does not fully explain the observed results. If bilateral coordination does not depend on cognitive resources, there is no reason to expect that the effect of dual tasking should be different bilaterally. Thus, we suggest that the increase in asymmetry is more consistent with the idea that the differences in left–right swing times are, in part, regulated by cognitive function.

Asymmetry was not affected by dual tasking in the healthy controls. These subjects have intact cognitive function and their gait is essentially “automatic” (Springer et al. 2006; Yogev et al. 2005), at least compared with the patient populations studied here. There are at least two possibilities to explain this insensitivity to dual tasking. If GA is regulated by lower-level processes when gait is automatic, one would anticipate no influence of dual tasking on GA, as observed in the present study. This is consistent with the idea that bipedal gait in man shares features of quadruped gait (Dietz 2002). Alternatively, even if cognitive resources contribute to the regulation of asymmetry in healthy older adults, perhaps the intact cognitive function allows these subjects to simultaneously allocate sufficient resources both to gait and to the dual task, without compromising either. While further study is needed to more fully clarify this point, it is interesting to note that while GA was sensitive to dual tasking in the patient populations, it was not associated with scores on the MMSE or with the attention or executive function indices.

In contrast to other measures of gait during dual tasking (Springer et al. 2006; Yogev et al. 2005), GA was not related to executive function or attention. Based on the capacity sharing theory, one could suggest that dual tasking might affect the performance of the cognitive tasks, in addition to or instead of gait. Perhaps, the lack of an association between GA and executive function may have occurred because some subjects allocated attention differently to each of these tasks. We could not fully test this idea since we did not measure the performance of the cognitive task alone. However, the association between executive function score and performance on the cognitive task is intriguing and may offer a clue to understanding the observed phenomena.

The present study has several limitations. Subjects in the control group tended to be a few years younger and walk faster than the other groups. Although age was not related to asymmetry and the inclusion of age in the statistical analysis did not alter the results, further studies should examine the possibility that age and gait speed may have partially modulated asymmetry. In the present study, we focused on one aspect of GA, in part based on the findings of Yang et al. (2006). Future investigations should also examine the relationship between this measure and other indices of asymmetry.

Possible clinical significance

Despite bearing statistical significance, the differences in GA between the groups and the response to dual tasking reflect relatively small changes in the left–right swing times. The question then arises whether such changes have clinical significance. The fact that as PD progresses, GA further increases, becomes even more pronounced among PD patients prone to freezing, and is highly sensitive to L-dopa deprivation supports the notion of a continuous scale that is related to disease severity. To more fully address this question, a longitudinal study could potentially be quite informative. It is also interesting to speculate about the potential contribution of bilateral asymmetry to fall risk. Support for this possibility is provided by the finding that asymmetry...
Acknowledgments  This work was supported in part by the National Parkinson Foundation, the Parkinson’s Disease Foundation, and by National Institutes of Health grants AG-14100, National Parkinson Foundation, the Parkinson's Disease Foundation, and by National Institutes of Health grants AG-14100, National Parkinson Foundation, the Parkinson’s Disease Foundation, and by National Institutes of Health grants AG-14100, National Parkinson Foundation, the Parkinson’s Disease Foundation, and by National Institutes of Health grants AG-14100, National Parkinson Foundation, the Parkinson’s Disease Foundation, and by National Institutes of Health grants AG-14100, National Parkinson Foundation, the Parkinson’s Disease Foundation, and by National Institutes of Health grants AG-14100, National Parkinson Foundation, the Parkinson’s Disease

References


