Interaction of age, cognitive function, and gait performance in 50–80-year-olds

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Abstract The variability of walking gait timing increases with age and is strongly related to fall risk. The purpose of the study was to examine the interaction of age, cognitive function, and gait performance during dual-task walking. Forty-two, healthy men and women, 50–80 years old, completed the Mini-Mental State Exam (MMSE) and Trail Making Test (TMT) to assess cognitive performance and were separated into groups by decade of life. They then performed dual-task walking, at a self-selected pace, on an instrumented treadmill during three cognitive loading conditions: (1) no cognitive load, (2) subtraction from 100 by 1s, and (3) subtraction from 100 by 3s. The treadmill recorded spatiotemporal gait parameters that were used to calculate the mean and coefficient of variation for each variable over ten strides. Time to complete the TMT was positively correlated with age, stride time, double-limb support time, and mediolateral instability and was inversely correlated with single-limb support time. Subjects in their 70s increased their stride time and double-limb support time during the most challenging dual-task condition (subtraction by 3s), whereas subjects in their 50s and 60s did not. Across conditions, the variability of stride length, stride time, and single-limb support time

was greatest in the 70s. Mediolateral instability increased only for subjects in their 70s in the subtraction by 3s condition. Reduced cognitive function with age makes it difficult for older adults to maintain a normal, rhythmical gait pattern while performing a cognitive task, which may place them at greater risk for falling.

Keywords Aging · Elderly · Falling · Dual task · Walking · Executive function

Introduction

Falls often cause serious injury, disability, and death, and the annual incidence of falls is approximately 30 % in persons over the age of 65 years, but rises to 50 % in persons over 80 years of age (Hester and Wei 2013). Elderly individuals who fall display poor strength, balance deficits, slow gait, poor cognitive function, and increased gait variability (Hausdorff et al. 2001b; Rossat et al. 2010; AGS 2001; Guimaraes and Isaacs 1980). These factors are comorbidities that likely interact to reduce the quality of movement in old age, predisposing the elderly to falling.

Gait variability is a measure of the rhythmicity of the gait cycle and has most often been used to examine temporal gait parameters (e.g., the variability of stride time, stance time, and swing time) in relation to both aging and fall risk (Hausdorff et al. 2001b; Gabell and Nayak 1984; Woollacott and Shumway-Cook 2002; Hausdorff et al. 1997). The variability of spatial gait parameters (e.g., step length and width) (Brach et al.

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2005) and kinetic gait parameters (e.g., ground reaction forces) (LaRoche et al. 2012) has also been studied with respect to walking performance in older adults. Variability can be reported as the standard deviation (SD) of a measure calculated over a series of sequential strides, or as the coefficient of variation (CV), a unitless measure that expresses this variability as a percent. Also, variability can be evaluated in terms of the frequency content of gait (Giakas and Baltzopoulos 1997) or by its fractal properties (Hausdorff et al. 2001a).

Regardless of how gait variability is measured, there is a consistently demonstrated increase in gait variability with aging, in diseases that affect the nervous system, and in older fallers in comparison to nonfallers (Hausdorff 2005). Hausdorff et al. (1997) reported that older adults with a history of falls exhibited temporal gait variability that was more than twice that of nonfallers. Individuals who display increased gait variability are slow to react to balance perturbations and, in a prospective study, were shown to have a fivefold likelihood of falling (Guimaraes and Isaacs 1980; Azar and Lawton 1964; Hausdorff 2005; Springer et al. 2006; Hausdorff et al. 2001b). Expounding factors that contribute to poor gait quality in older adults is therefore an important area of research that has the potential to help reduce the risk of falling in this population.

One method used to study locomotor control of older adults is performing a dual task that simultaneously challenges motor and cognitive function. The three underlying assumptions for the dual-task paradigm include the following: (1) the nervous system has a limited central processing capacity; (2) performing a task requires part of that processing capacity; and (3) if two tasks share the processing capacity, the performance in one or both tasks can be disturbed if the processing capacity is exceeded (Lajoie et al. 1993) (Fig. 1). A dual task as simple as walking and talking has shown that older adults who stop walking when they talked had poor mobility, less safe gait, decreased independence in activities of daily living, and increased incidence of falls (Lundin-Olsson et al. 1997). A study by Dubost et al. (2006) showed that stride time CV of older adults nearly doubled from 1.61 ± 0.61 % when walking at self-selected speed to 2.90 ± 1.51 % with the addition of a verbal fluency task. During dual-task walking, people of all ages exhibit increased gait variability, but this phenomenon is more pronounced in the elderly (Hausdorff et al. 1997; Hollman et al. 2007).

Fig. 1 Conceptual model of the dual-task walking paradigm compares the central processing requirements of walking and cognitive tasks between young and older adults. Insert text provides examples of the subcomponent central processing requirements of cognitive and walking tasks

Lajoie et al. (1993) report that while walking is a “highly practiced and repetitive action ... balance control during walking is not automatic” requiring a portion of central processing. With aging, there is both a decrease in central processing capacity of the nervous system (Verhaeghen and Cerella 2002) and an increase in attentional demand for motor and cognitive tasks (Woollacott and Shumway-Cook 2002). Executive function (EF) refers to a set of cognitive skills that are necessary to plan, monitor, and execute a sequence of goal-directed, complex actions (Royall et al. 2002). Individuals with poor EF have been shown to have greater stride time variability while dual-task walking than those with normal EF. Linking cognitive performance and fall risk, Herman et al. (2010b) showed that a low level of EF was associated with a threefold risk of falling over a 2-year period.

The purpose of the present study was to examine how age, EF, and level of cognitive loading interact to affect gait performance in older adults. It was hypothesized that the oldest subjects would demonstrate poorer EF, slower preferred walking speed, and spatial and temporal gait parameters that characterize elderly gait (e.g., shorter stride length and wider stride width). Along with a more cautious gait pattern, it was expected that the oldest subjects would demonstrate greater variability of

spatiotemporal gait parameters and that this variability would be directly related to EF and level of cognitive loading during dual-task walking.

Methods

Subjects

Forty-two, independent, community-dwelling men and women between 50 and 80 years old, who were able to walk without assistance, were included in the study. Volunteers were excluded if they had neurological or orthopedic deficits, received a score of <8 on the Short Physical Performance Battery (SPPB) (Guralnik et al. 2000), or were unable to complete the research protocol. Subjects were divided into three groups by current decade of life. Group 1 consisted of five men and nine women age 50–59 years (50s), group 2 consisted of six men and nine women age 60–69 years (60s), and group 3 consisted of six men and seven women age 70–79 years (70s).

First visit

The protocol involved two visits. During the initial visit, subjects provided written, informed consent to participate in the study, which was approved by the university's institutional review board. Subjects also had to furnish a physician clearance form that demonstrated they were free from major disease and it was safe for them to participate in this walking study. To assess cognitive status, subjects completed both the Mini-Mental State Exam (MMSE) (Herman et al. 2010a; Folstein et al. 1975) and Trail Making Test (TMT) (Sanchez-Cubillo et al. 2009; Tombaugh 2004). The MMSE involves a series of questions and instructions given to the participants to assess their orientation, memory, attention, recall, and language abilities (Folstein et al. 1975). The TMT was used to assess central processing and executive function by testing task switching ability, visuomotor speed, and working memory (Sanchez-Cubillo et al. 2009). The TMT part A (TMT-A) requires participants to sequentially draw lines between numbered circles that are randomly arranged on a page as fast as possible and TMT part B (TMT-B) requires them to connect numbered and lettered circles in an alphanumeric sequence (1-A-2-B-3 etc...). Cognitive tests were followed by the SPPB to evaluate

functional mobility through standing balance, usual gait speed, and chair rise tests (Guralnik et al. 1994). Next, subjects completed a 10-min habituation walk at 0.8 m s^{-1} on an instrumented gait analysis treadmill (Gaitway II, Kistler Instrument Corp., Amherst, NY, USA). At the end of the habituation walk, preferred walking speed was identified by asking participants to “choose the speed you would normally walk down the street when going to the store” while the investigators slowly increased the speed from 0.5 m s^{-1} .

Second visit

The second visit was scheduled within 1 week of the first and began by measuring height and body mass. After stepping onto the treadmill, an upper body harness was fit to the subjects' torso and connected to an overhead support system to support body weight in the event of a fall. The line connecting the harness to the support system was kept slack and slightly posterior to the subjects such that it did not interfere with their normal movement patterns. Next, a 5-min warm-up walk was completed on the treadmill at each subject's preferred speed determined during visit 1. Subjects were instructed to “look, walk, and talk straight ahead” during the test, but were not instructed on how to allocate attention between walking and cognitive tasks. Participants performed the following three tasks while walking: (1) single task, no cognitive load; (2) dual task, serial 1s—counting down from 100 by 1s; and (3) dual task, serial 3s—counting down from 100 by 3s (LaPointe et al. 2010). The serial 3s subtraction task has been shown to elicit the greatest number of calculation errors during dual-task walking in older adults and was the highest cognitive load condition in this study (Srygley et al. 2009). At the end of the warm-up, subjects continued to walk at their preferred speed and completed each of the three tasks in a counterbalanced, random order. Subjects walked for 10s while performing each task before 15s of gait data was collected that provided approximately ten strides (20 steps), similar to previous studies in our laboratory (LaRoche et al. 2012; LaRoche et al. 2011). Ten strides have been shown to be a sufficient number of strides to reliably measure gait variability (Brach et al. 2008; Lord et al. 2011), particularly during continuous walking (Galna et al. 2013), and allowed gait data to be collected in a single, nonfatiguing, uninterrupted trial. After gait data were collected, subjects continued walking for a period

of 1 min to reestablish their normal gait pattern before completing the next task.

The treadmill's deck contained two force plates that provided vertical ground reaction force (vGRF) and center of pressure measurements (COP) independently for each foot. Using these measures, spatial and temporal gait parameters were calculated by the software (Gaitway v. 2.0.8.50, Kistler Instrument Corp., Amherst, NY, USA) under each condition. While the software provides a multitude of gait variables, we identified six variables a priori that have been associated with mobility and fall risk in older adults and were most likely to be affected by cognitive function during dual-task conditions. These were three spatial gait variables including stride length, mediolateral foot strike location, and stride width (Brach et al. 2001) and three temporal gait variables including stride time, single-limb support time, and double-limb support time (Lajoie et al. 1993; Hausdorff et al. 1997). Both the mean of each gait parameter and the variability of each gait parameter were compared between age groups and across cognitive loading conditions.

Using COP data and treadmill belt speed, the software determined stride length as the distance from a foot's initial heel contact to the following heel contact of the same foot. Foot strike location was the average mediolateral position of the COP during foot-ground contact and was used to assess the lateral stability of the subject with respect to the center of the treadmill. Stride width was calculated by using the average distance between a foot's COP and the opposing foot's COP at the next foot strike. Stride time was the duration from the initial heel contact of one foot to heel contact of the same foot at the completion of a single gait cycle (e.g., time from right heel strike to right heel strike). Double-limb support time was calculated by comparing vGRF data between feet to determine the portion of stance when the body was supported by both limbs, and single-limb support time was the portion of stance when the body was supported by only one limb. Double support time and single support time were normalized as percent of the gait cycle (%GC) by dividing each variable by the stride time and multiplying by 100 %.

Statistical analysis

For each condition, gait variables for each leg were exported from the Gaitway software to a spreadsheet program that was used to calculate the mean, SD, and

CV for each stride parameter, across the multiple strides within a trial. The CV was used to provide a unitless measure of the variability of each gait parameter, which was calculated as:

$$CV = (\text{standard deviation of strides} / \text{mean of strides}) \times 100\% \quad (1)$$

The SD of foot strike location was used in place of CV because the mean position of the foot on the treadmill is irrelevant and would bias the CV. Normality of the data was confirmed with the Kolmogorov-Smirnov and Levene statistics (IBM SPSS Statistics, v. 20, IBM Corporation, Armonk, NY, USA). Group differences for descriptive variables were determined using a one-way analysis of variance (ANOVA), with Tukey's post hoc analysis to identify the source of the group differences. A repeated measures analysis of variance (RMANOVA) was used to assess the combined effects of age and cognitive load on the mean scores for spatiotemporal gait parameters, and a second RMANOVA was similarly used to test the effects on the variability of spatiotemporal gait measures. Tukey's post hoc tests were used to examine differences in main effects for age group and cognitive loading condition. Independent samples *t* tests were used when appropriate to determine differences between age groups for a given level of cognitive loading. The Pearson product moment statistic was used to assess the relationships between tests of cognitive function (TMT and MMSE), age, and gait performance, but only for the most challenging dual-task condition (serial 3s). Linear regression was used to explore the relative contribution of age and EF to stride length variability under the serial 3s condition. Statistical significance was set at $P \leq 0.05$ for all tests.

Results

Subject characteristics

Subject anthropometric characteristics including mass, height, and body mass index (BMI) were similar between groups (Table 1). Subjects in their 70s had 30 and 35 % longer TMT-A times compared to the 50s and 60s, respectively ($P < 0.001$). Those in their 70s also had 32 % longer TMT-B times compared to the 50s ($P =$

Table 1 Subject descriptive characteristics

	50s (<i>N</i> =14)	60s (<i>N</i> =15)	70s (<i>N</i> =13)	<i>P</i>
Age (years)	55.71±3.07	63.87±2.64	74.08±2.36	<0.001 ^{*,†,§}
Mass (kg)	73.76±17.80	73.75±14.44	69.09±14.48	0.674
Height (m)	1.73±0.09	1.69±0.09	1.66±0.10	0.165
BMI (kg m ⁻²)	24.43±5.15	25.76±5.78	24.69±3.34	0.745
MMSE score	28.86±1.17	29.20±1.01	28.92±1.19	0.684
TMT-A time (s)	24.27±4.31	26.20±7.58	37.25±8.47	<0.001 ^{*,§}
TMT-B time (s)	45.08±14.61	56.37±28.02	66.57±14.72	0.033 [*]
SPPB score	11.79±0.43	11.60±0.74	11.08±1.38	0.130
Preferred overground walking speed (m s ⁻¹)	1.12±0.14	1.03±0.18	1.02±0.18	0.235
Preferred treadmill walking speed (m s ⁻¹)	1.18±0.11	1.10±0.18	0.97±0.19	0.007 [*]

Values are mean±SD

BMI body mass index, *MMSE* Mini-Mental State Exam, *TMT-A* Trail Making Test Part A, *TMT-B* Trail Making Test Part B, *SPPB* Short Physical Performance Battery

^{*} $P<0.05$, significant difference between 50s and 70s; [†] $P<0.05$, significant difference between 50s and 60s; [§] $P<0.05$, significant difference between 60s and 70s

0.025). There were no significant differences between groups for MMSE score. Self-selected, preferred treadmill speed was 18 % slower for those in their 70s versus 50s ($P=0.005$) and was not statistically different between the 60s and the other age groups ($P>0.05$). There were no subtraction errors for any subject during the serial 1s condition; however, in the serial 3s condition, the 70s group had a greater number of errors (0.85 ± 0.89) than the 60s (0.07 ± 0.26 , $P=0.018$) but not more than the 50s (0.50 ± 0.86 , $P=0.248$).

Association of cognitive tests and spatiotemporal gait performance

TMT-A time was significantly correlated with age ($r=0.58$, $P<0.001$), as was TMT-B time ($r=0.42$, $P=0.003$), whereas MMSE score was not correlated with age ($r=-0.01$, $P=0.486$). Under the serial 3s cognitive loading condition, the time needed to complete the TMT-A test was positively correlated with stride time ($r=0.42$, $P=0.003$), double-limb support time ($r=0.30$, $P=0.026$), and foot strike location SD ($r=0.47$, $P=0.001$) and was inversely correlated with single-limb support time ($r=-0.34$, $P=0.013$). The time to complete the TMT-B was not associated with any gait or gait variability measure during the serial 3s condition. Under the serial 3s condition, MMSE score was inversely correlated to single-limb stance time CV ($r=-0.29$, $P=0.033$). Linear regression using age and TMT-A to

predict stride length CV in the serial 3s condition revealed that age was significant in the model (partial correlation=0.40, $P=0.01$) and TMT-A was not (partial correlation=-0.07, $P=0.66$). Collinearity diagnostics generated eigenvalues of 0.047 for age and 0.006 for TMT-A with condition indices of 7.91 and 22.53, respectively.

Spatial and temporal gait parameters

Results of the RMANOVA examining the effect of age and cognitive load on gait performance during dual-task walking are reported in Table 2. When averaged across age groups, stride time increased from 1.14 ± 0.02 s in the single-task condition, to 1.16 ± 0.02 s ($P=0.044$) in the serial 1-s condition, to 1.17 ± 0.02 s ($P=0.029$) in the serial 3s condition (Fig. 2a). Similarly, stride length increased from 122.0 ± 2.7 cm, to 123.7 ± 2.8 cm ($P=0.08$), to 125.8 ± 2.6 cm ($P=0.035$) across cognitive loading conditions (Fig. 2d). Averaged across conditions, stride length was longer in the 50s (132.1 ± 16.5 cm) than in the 70s (116.2 ± 17.1 cm, $P=0.043$) with no differences between the 60s (123.1 ± 16.01 cm, $P>0.05$) and the other age groups. Likewise, double support time ($P=0.028$) increased with age from 13.11 ± 0.61 %GC in the 50s to 15.55 ± 2.36 %GC in the 70s ($P=0.008$), with no differences between the 60s and other age groups (14.15 ± 2.20 % GC, $P>0.05$). An age group by cognitive load interaction occurred

whereby subjects in their 70s had an increase in double support time during the serial 3s condition and younger age groups did not (Fig. 2c).

Variability of spatial and temporal gait parameters

Averaged across groups, single-limb support time CV was lower in the serial 3s condition ($3.60 \pm 0.98\%$) than in the single-task ($5.16 \pm 1.83\%$, $P=0.004$) and serial 1s ($5.93 \pm 2.69\%$, $P=0.007$) conditions (Fig. 3b). Also, foot strike location SD was higher in serial 3s (1.94 ± 0.57 cm) than in single-task (1.62 ± 0.30 cm, $P=0.041$) and serial 1s (1.519 ± 0.35 cm, $P=0.018$) conditions (Fig. 3f). Stride length CV was higher in the 70s ($2.53 \pm 0.81\%$) than in the 50s ($1.50 \pm 0.78\%$, $P=0.002$) and 60s ($1.69 \pm 0.76\%$, $P=0.007$) age groups (Fig. 3d). Averaged across conditions, there was a statistical trend ($P=0.066$) for greater stride time CV (Fig. 3a) in the oldest group. In the same way, single-limb support time CV was greater in the 70s ($5.96 \pm 2.14\%$) than in the 50s ($3.67 \pm 2.07\%$, $P=0.007$) with no differences between the 60s and the other age groups ($5.05 \pm 1.99\%$, $P<0.05$) (Fig. 3b). An age group by cognitive load interaction existed that showed subjects in their 70s had an increase in foot strike location variability during the serial 3s condition and the younger subjects did not (Fig. 3f). Double support time variability and stride width variability did not differ between age groups or cognitive loading conditions ($P>0.05$) (Fig. 3c, e). When TMT-A was used as a covariate in the RMANOVA, the significant main effect of cognitive load for single support time CV and foot strike location CV and the cognitive load by age group interaction for foot strike location SD were eliminated ($P>0.05$), but the significant age group effects remained and stride time CV became significantly different between age groups ($P=0.018$).

Discussion

The current study contributes to the knowledge of the relationship between age, cognitive function, and gait performance for a number of reasons. This study stratified the response of older adults to a dual-task walking protocol by decade (50s, 60s, and 70s), whereas many earlier studies compare a

single group of older adults to a much younger group (Siu et al. 2008; Priest et al. 2008; Springer et al. 2006; Srygley et al. 2009), and this study tested three levels of cognitive loading to determine if there were age by cognitive load interactions. Walking speed was self-selected by the participant and was held steady under single and dual-task conditions, which eliminated changes in speed across conditions as a confounding factor. Last, this research examined a comprehensive set of spatial and temporal gait variables known to be related to gait performance and falling in older adults and recorded gait data during a single, uninterrupted walking bout.

Important findings of the study were that measures of cognitive function were significantly correlated to altered gait during dual-task walking, and older subjects adopt slower walking speeds, shorter stride lengths, and spent more time in double support than their younger peers. There was a difference in the response to dual-task walking for subjects in their 70s who increased their stride time and double-limb support time during the most challenging dual-task condition (serial 3s), whereas subjects in their 50s and 60s did not. Similarly, foot strike location variability increased for subjects in their 70s in the serial 3s condition that indicated that they had a more difficult

Table 2 Repeated measures analysis of variance results on the effect of age group and cognitive load on gait performance during dual-task walking

	<i>P</i> values		
	Age group effect	Cognitive load effect	Age group $\times$ cognitive load interaction
Stride time	0.121	0.041*	0.159
Singlesupport time	0.324	0.535	0.327
Double support time	0.028*	0.174	0.031*
Stride length	0.053	0.039*	0.160
Stride width	0.635	0.644	0.205
Stride time CV	0.066	0.174	0.637
Single support time CV	0.022*	0.006*	0.544
Double support time CV	0.785	0.324	0.315
Stride length CV	0.004*	0.398	0.825
Stride width CV	0.370	0.154	0.983
Foot strike location SD	0.168	0.015*	0.048*

* $P<0.05$, denoting significant difference

time maintaining spatial orientation while simultaneously walking and performing a cognitive task. A similar trend existed for stride time variability and stride length variability that suggests a reduction in gait rhythmicity while cognitively challenged that occurred most notably in the oldest subjects. The hypothesis that the oldest subjects, with the poorest EF, would alter gait most under dual-task walking conditions was thus supported for a number of spatiotemporal gait parameters.

Executive function and gait performance

The TMT was used to measure EF, task switching abilities, and visuomotor skills, and this measure was positively correlated to age and inversely related to gait performance. A review by Buckner (2004) shows that cognitive function changes minimally from 50 to 70 years of age and then significantly decreases from 70 to 90 years of age (Buckner 2004). The abrupt decline in cognitive function may occur as older adults

retire from the workplace and move to an environment that includes less mental and physical stimulation (Ybarra et al. 2008). The mechanisms associated with reduced EF in the elderly, and the potential effects on gait, have been recently reviewed by Yogev-Seligmann et al. (2008) and include age-associated degeneration of frontal lobe structures including white matter lesions, loss of gray matter, reduced dendritic branching, and reduced dopaminergic activity.

The time needed to complete TMT-A was associated with increased stride time, greater double-limb support time, shorter single-limb support time, and greater mediolateral instability during walking, which are characteristics of elderly gait (Winter et al. 1990). The findings of the present study suggest that a small reduction in EF in individuals in their 70s, even within the normative range (Tombaugh 2004), may be enough to reduce ability to maintain a normal, steady gait when cognitively challenged. Other researchers have shown that TMT

Fig. 2 Comparison of stride time (a), single support time (b), double support time (c), stride length (d), and stride width (e) between groups under single-task walking (single), low cognitive load dual-task walking (counting backwards by ones, Dual-1s), and higher cognitive load dual-task walking (counting backwards

by threes, Dual-3s) conditions. %GC percent of gait cycle. Values are mean±SD. * $P<0.05$, significant difference between 50s and 70s; † $P<0.05$, significant difference between 50s and 60s; § $P<0.05$, significant difference between 60s and 70s

Variability of Temporal Gait Parameters

Variability of Spatial Gait Parameters

Fig. 3 Comparison of gait variability for stride time CV (a), single support time CV (b), double support time CV (c), stride length CV (d), stride width CV (e), and foot strike location SD (f) between groups under single-task walking (single), low cognitive load dual-task walking (counting backwards by ones, Dual-1s), and higher cognitive load dual-task walking (counting backwards by

threes, Dual-3s) conditions. *CV* coefficient of variation, *SD* standard deviation. Values are mean±SD. * $P<0.05$, significant difference between 50s and 70s; † $P<0.05$, significant difference between 50s and 60s; § $P<0.05$, significant difference between 60s and 70s

time is associated with the ability to allocate attention, with age-related reductions in walking speed, increased gait variability, and poorer cognitive performance during dual-task conditions (Siu et al. 2008; Srygley et al. 2009; Montero-Odasso et al. 2009; Coppin et al. 2006; Yogev-Seligmann et al. 2010). The TMT may therefore be a simple screening tool that is sensitive to both declining cognitive and physical function in older adults.

It is not known if increased age and decreased EF independently influence movement quality, or if they are tightly coupled. To attempt to answer this question, we repeated the RMANOVA for the gait variability measures with TMT-A (our measure of EF) as a covariate. The significant main effects of cognitive loading condition and the age group by cognitive load interaction were eliminated, which demonstrated that EF was partly responsible for the age-associated decline in gait performance seen during dual-task walking.

Controlling for EF enhanced the age group effects indicating that differences in EF within age groups contributed to the between-subject variability in gait performance. When age and TMT-A time were used as predictor variables in linear regression, the partial correlations revealed that age was the primary factor predicting stride length variability under a dual-task condition. This indicates that other deficits of aging (strength, balance, coordination, vision, somatosensory, etc.) may have contributed more to increased gait variability during dual-task walking than EF. However, collinearity diagnostics in the regression analysis (eigenvalues near zero along with high condition indices) indicated that age and TMT-A were collinear. Taken together, these post hoc analyses suggest that while both age and EF are independently related to poor gait quality, it may not be possible to separate their effects as increasing age and declining executive function occur concurrently.

Cognitive loading and stride kinematics

Results of the current study show that performing a cognitive task while walking alters gait of healthy, community-dwelling, older adults, and probably more so in the oldest individuals. The data indicate that the 70s group increased stride length, increased stride time, and increased the time spent in double-limb support in an effort to maintain their stability and orientation during the most challenging dual-task condition. We speculate that these subjects did not have the level of EF needed to simultaneously perform both the walking and cognitive tasks, and they prioritized the subtraction task over the maintenance of gait stability. This theory is supported by the small number of subtraction errors recorded in this condition. If a subconscious prioritization of cognitive tasks over stability and gait occurs in old age, it may predispose the oldest subjects to a loss of balance when distracted.

With age, decreased EF may lessen the attentional resources available to process both the motor planning and cognitive aspects of gait (van Iersel et al. 2007). It has been suggested that older adults adopt slower gait to minimize motor planning and allow their mind to utilize their diminished cognitive attention, with consequent increases in stride-to-stride variability and risk for falls (Montero-Odasso et al. 2009). It has been shown that walking on a treadmill requires some conscious attention and that individuals will reduce walking velocity while performing a second task (Montero-Odasso et al. 2009; Regnaud et al. 2006). The subjects in their 70s were the only group to choose slower treadmill speeds compared to their overground speeds, possibly as a compensatory mechanism to deal with the added challenge of treadmill walking.

Cognitive loading and gait variability

Although the variability of stride length, foot strike location, single-limb support time, and stride time were higher in the 70s group, the variability of these temporal gait measures was only moderately influenced by the addition of a cognitive load in the dual-task walking conditions. While the mean stride length CV and stride time CV appear to increase with cognitive loading in the 70s group, the interaction was not statistically significant because of the high between-subject variability (see SD error bars in Fig. 3 for the 70s group). It was our observation that some subjects in the 70s group had a

very difficult time maintaining a steady gait in the serial 3s condition, whereas others completed the trial with limited difficulty. The group possessed a range of physical and cognitive capacities and it is likely that this task differentially challenged the subjects with the poorest function.

The modest effect of dual-task loading on temporal gait variability may have also occurred because the assessment was performed while walking on a treadmill, at a fixed speed, and may have been different if the subjects had performed the dual-task trials overground where their speeds would not have been kept constant. For example, counting backwards from 100 by ones has been shown to reduce gait speed of older adults with mild cognitive impairment by 28 % (Montero-Odasso et al. 2009). In the absence of a dual task, Van Emmerik et al. (1999) demonstrated that stride time variability increases as speed decreases. Similarly, Dubost et al. (2006) showed that the increase in stride time variability under dual-task conditions was a product of both a verbal fluency task and the decreased walking speed that occurred in this dual-task condition. It is therefore plausible that much of the increased temporal gait variability usually seen during dual-task walking overground is a result of reduced speed.

An unexpected finding of this study was that single-limb support time variability decreased in all groups with an increase in cognitive loading. It is not clear what the source of the reduced variability is, but it may have occurred because of the increase in stride time that occurred in the serial 3s condition. Single support time variability was calculated using time in seconds (not normalized as percent of gait cycle), which increased concurrently with stride time in the serial 3s trial. It is possible that as the magnitude of single-limb support time increased, the reliability of its measurement between strides increased and contributed to the reduced variability seen in the serial 3s condition. Nevertheless, the 70s group demonstrated a higher level of single-limb support time variability in the serial 3s condition than other age groups.

Cognitive loading and balance control

Gabell and Nayak (1984) originally proposed that the variability of stride width and double support time is primarily determined by balance control. Two spatial gait variability parameters related to balance (i.e., foot strike location SD and stride length CV) were more

affected by age and cognitive loading than the temporal aspects, even though people normally utilize a “posture first” strategy to prioritize balance ahead of other tasks (Yogev-Seligmann et al. 2008). We hypothesized that the dual-task conditions would challenge balance control resulting in a wider stride width, increased time spent in double-limb support, along with a more variable stride width and greater foot strike location variability (our marker of mediolateral instability). Double support time and foot strike location variability increased in the 70s group in the serial 3s condition, whereas there was no effect of cognitive load on stride width or stride width variability. In fact, the older subjects walked with a narrower stride width under the most challenging conditions, which was likely a suboptimal strategy. Guimaraes and Isaacs (1980) showed that elderly fallers walked more slowly, with a shorter step length, narrower stride width, and increased step length variability compared to their nonfalling peers, a pattern similar to this study’s oldest subjects. The greater mediolateral instability in the 70s group may partly be explained by a linear decline with age in the mechanical work performed at the hip and ankle during walking, which causes a decreased capacity to control body movement in the oldest individuals (Ko et al. 2010).

Fall risk in older adults has been studied from the perspective of muscle weakness, gait performance, balance, visual acuity, and cognitive function (AGS 2001). This study demonstrates that when older individuals are challenged by simultaneously performing a cognitive and physical task, walking performance and balance control are diminished. A comprehensive reading of the fall risk literature illustrates that it is impossible to separate the effects of the comorbidities of aging, despite researchers’ attempts to do so. With aging comes a generalized decline in sensory, central nervous, motor control, musculoskeletal, cardiopulmonary, and metabolic function, along with changes in body composition, that predispose older individuals to falling. It is likely that the elderly are aware of their declining function and slow and alter gait to operate within their diminished capacities; however, this awareness may be compromised in those with cognitive dysfunction. To reduce the risk of falls, it is therefore important to identify cognitive and physical weaknesses, attempt to improve these weaknesses, and counsel older adults about limiting the number of challenges while walking.

Limitations and future research

The sample consisted of healthy, community-dwelling, older adults without mobility or cognitive dysfunction between the ages of 50 and 80 years. Had older individuals (80–100 years) and those with physical or cognitive dysfunction been included in the study, the relationship between executive function (EF) and gait variability during dual-task walking may have been more pronounced. Also, walking was performed on a treadmill, which limits the external validity of this study to some extent, although treadmill walking has been shown to be biomechanically similar to overground walking (Parvataneni et al. 2009). The reliability of gait variability measurement is believed to improve as the number of strides increases from a few (Brach et al. 2008) to 25 or more (Galna et al. 2013; Hollman et al. 2010), and thus, this study could have been improved by collecting gait data over a longer period. The lower reliability seen for gait variability measures than for spatiotemporal measures (Brach et al. 2008) could have contributed to the lack of consistent findings seen in this study. Nevertheless, gait variability metrics calculated in this manner using as few as five to six strides have been shown to be sensitive to health, ability to perform activities of daily living, mobility, balance, and physical activity status (Brach et al. 2008).

Conclusions

This study showed that a lower level of EF is associated with reduced gait performance in healthy older adults. Increased cognitive load during dual-task walking resulted in increased stride length, stride time, double-limb support time, and decreased mediolateral stability, particularly for subjects in their 70s. These findings suggest that the eighth decade of life is a time when age, cognitive function, and physical performance interact most notably to disrupt the quality of movement. Health screening of older adults should therefore incorporate measures of EF, like the Trail Making Test, and assess walking performance under dual-task conditions, in order to detect declines in function that may predispose older persons to falling.

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