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Human Kinetics
ORIGINAL RESEARCH

Gait Coordination Deteriorates in Independent Old-Old Adults

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Human gait is symmetric and bilaterally coordinated in young healthy persons. In this study, we aimed to explore the differences in bilateral coordination of gait as measured by the phase coordination index (PCI), gait asymmetry, and stride time variability of gait between four age groups. A total of 44 older adults were recruited: nine young-old (age 70–74 years), 26 old (age 75–84 years), nine old-old (>85 years and older), and 13 young adults (age 20–30 years). Subjects walked on a treadmill; walking speed was systematically increased from 0.5 to 0.9 m/s in steps of 0.1 m/s. There were marginal effects of age on PCI, significant main effects of walking speeds without interaction between walking speeds and age group. A difference in PCI could distinguish between young's and late aging group, and only during their preferred treadmills walking speed. This study explicitly shows that bilateral coordination of walking is modified by gait speed, and deteriorates only at a very old age.

Keywords: aging, bilateral coordination of gait, gait asymmetry, gait speed, stride time variability

Across all ages, walking is a fundamental physical activity. Aging is characterized by functional changes in the sensory, neurological, and musculoskeletal systems, affecting motor tasks including gait and postural balance (Guralnik et al., 1994). Most of the falls among older adults occur while walking (Berg, Alessio, Mills, & Tong, 1997; Nevitt, Cummings, & Hudes, 1991). Balance control is essential for safe and independent daily activities, including standing and walking. Deterioration of the balance control can cause posture and gait impairments, hence increase the risk for falling (Rubenstein, 2006). Even independent older adults are affected from deterioration of balance and walking ability (Alexander, 1996); however, this substantial decline does not become evident until they fall (Woollacott & Tang, 1997).

It has been shown that aging is associated with increases in step width (Maki, Holliday, & Topper, 1994) and stride frequency, as well as decreased stride velocity, stride time, and step length, while walking (Judge, Davis, & Ounpuu, 1996; Schrager, Kelly, Price, Ferrucci, & Shumway-Cook, 2008). The average gait speed declines 12–16% per decade from the age of 70 years (Judge et al., 1996). The above studies suggest that older adults typically display different gait characteristics than young's, but the cause of this increase is unclear (England & Granata 2007; Jordan, Challis, & Newell, 2007). Slower walking leads to greater gait variability even in young's, but slow speeds are also typical in older adults. As old and young adults walk in different velocity and gait parameters changes with walking velocity, a dilemma arises with respect to the proper way to compare data collected at different walking velocities. The changes in gait characteristics in older adults may result from slower walking speeds (Maki, 1997) or possibly from other factors related to aging. In most research studies on the aging populations, subjects are usually grouped into one older group spanning several decades. In this study, we investigate gait within an aging group, as well as between the aging groups and young participants. We used a dynamic approach where the gait velocity is controlled by treadmill across different walking speeds (Barak Wagenaar, & Holt, 2006; Wagenaar & Beek, 1992), comparing age-related differences in gait asymmetry (GA) and phase coordination index (PCI) in different walking speeds. Recent studies observed that gait variables are account for the long-term control of gait rhythmicity, such as gait variability—that is, stride to stride time variability—are associated with increased risk of falling in older adults (Hausdorff, Rios, & Edelberg, 2001). Temporal gait parameters also account for the long-term control of bilateral functions of gait, which also been implicated in the risk of falling. For example, Yogev, Plotnik, Peretz, Giladi, and Hausdorff (2007) found that increased GA, as measured by comparing a series of left and right swing times, is an indication in older subjects with the tendency to fall. GA might reflect the degree of similarity in motor function of the legs (Plotnik, Giladi, & Hausdorff, 2007). Healthy young adults show delicate GA in spatial–temporal parameters (Sadeghi, Allard, Prince, & Labelle, 2000). Old adults showed significantly higher temporal GA compared with young adults (Plotnik et al., 2007). Likewise, impaired bilateral coordination of gait as measured by the PCI, a metric that quantifies the long-term consistency and accuracy in generating antiphased left–right stepping, is associated with aging (Plotnik et al., 2007). Yet in healthy adults (old and young), GA, gait variability, and gait speed are weakly correlated with PCI (Plotnik et al., 2007). During preferred slow and fast overground walking, the GA is stable, while PCI deteriorates when the subjects walked slow, suggesting that an increase in attention resources required the regulation of slow walking (Plotnik, Bartsch, Zeev, Giladi, & Hausdorff, 2013).

Gait becomes asymmetric during dual tasking in fallers, compared with nonfallers older adults, indicating that certain aspects of gait may depend on cognitive function and attention

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(Yogev et al., 2007), which frequently decline among older adults. However, most of the above studies explored age-related changes in GA and PCI in older adults younger than 80 years old or directed toward high-risk populations; although the most growing demographic is the old adults aged 80 years and older who live independently in the community (Centers for Disease Control and Prevention, 2013; Vaupel, 2010). Furthermore, the linear trend that life expectancies have followed for over a century is set to continue. Therefore, for an early risk detection and prevention, a better way to investigate gait changes is studying gait behavior in older adults aged 80 years and older who live independently in the community and have not yet fallen. Thus, we aimed to explore the differences in GA, PCI, and stride time coefficient of variance (CV) of gait in old-old (OO) subjects (i.e., >85) and to compare with young, old-young's, and old. We hypothesized that compared with young's old–young's and the old groups, the OO group will present (a) higher PCI with a positive interaction with walking speed, (b) higher GA without interaction to walking speed, and (c) increased stride time variability with a positive interaction to walking speed.

Methods

Subjects

A total of 44 old adults were recruited from senior community centers in the Beer-Sheva region, Israel. Nine were young-old (YO), 70–74 years old; 26 were old (O), 75–84 years old; and nine were OO >85 years old. Older adults showed high function and cognitive status (mean Performance-Oriented Mobility Assessment [POMA] = 26.8 and mean Mini-Mental State Examination [MMSE] = 28.9; Table 1). Thirteen young adults (Y) were recruited from a university population. Eligibility criteria for older adults were: 70 years or older; independently ambulatory; and a MMSE score higher than 24. Exclusion criteria included any orthopedic, neurological, or severe cardiovascular disorders that could interfere with gait. The study was approved by the Helsinki committee at the Barzilai University Medical Center, Ashkelon, Israel (ClinicalTrials.gov Registration number #NCT01439451). All subjects signed an informed consent statement. After signing on the consent forms, MMSE (Folstein, Robins, & Helzer, 1983); fear of falling (Yardley & Smith, 2002); and POMA (Tinetti, 1986) were performed. In addition, participants were asked to recall how many times they had fallen in the past 12 months.

Study Protocol

Subjects were instructed to walk on a treadmill, wearing their own walking shoes, with their hands free to swing; there were no handrails on the treadmill. Familiarization with the treadmill was achieved for each subject by 4–7 min of walking prior to data collection. To prevent injury if loss of balance occurred during the treadmill walking, the subject wore a loose safety harness that could arrest the fall but that allowed the subject to walk comfortably without suspension (Figure 1).

The following instruction was given to the subjects: “Walk as naturally as possible at your preferred stride frequency.” The treadmill's walking speed was systematically increased from 0.5 to 0.9 m/s in steps of 0.1 m/s, and subsequently, decreased in similar increments. Each walking speed condition was maintained for 40 s. This included 10 s for subject adaptation to a new speed condition followed by 30 s for motion data collection. If the subject felt unsafe during one of the walking conditions, the treadmill speed was decreased to a lower walking speed, and the data for the walking speed where the subject felt unsafe were not included in the data analysis. Following the data collection period and a 15-min time break, the participants were asked to walk again in the lowest treadmill's velocity (0.5 m/s), and the treadmill's velocity was systematically increased in steps of 0.1 m/s. The participants were instructed to report their preferred/most comfortable treadmill walking speed.

Kinematic Analysis

Three-dimensional (3D) kinematic data were collected through the ariel performance analysis system (Ariel Dynamics Inc., Trabuco Canyon, CA), which can provide kinematic analysis of a motion sequence. Two video cameras were placed at an angle of 45°, 7 m in front of the treadmill, and they recorded the motion of eight reflective markers placed on the body. The markers were attached to the midline of the anterior aspect of the ankle joints, the anterior superior iliac spines, the shoulders' acromion process, and the radial styloid process. The marker locations were sampled simultaneously by the cameras at a frequency of 60 Hz. Views from the two cameras were mapped onto a 3D coordinate system by the

Table 1 Subjects' Characteristics: Descriptive Statistics and Group Comparisons

Characteristic	Young	Young-old	Old	Old-old	*p* value
Age	26.23 ± 1.2	71.90 ± 1.9	79.85 ± 2.3	87.22 ± 1.9	<.001
Gender (male/female)	6/7	4/5	8/18	3/6	<.001
Height (cm)	170.31 ± 10.3	164.39 ± 7.5	157.57 ± 8.6	159.92 ± 14.9	<.001
Weight (kg)	65.00 ± 12.3	76.07 ± 14.6	64.95 ± 12.1	69.55 ± 15.6	<.001
Number of medications/day	0.00 ± 0.00	3.59 ± 1.4	3.72 ± 1.8	4.47 ± 2.4	.053
MMSE	N/A	29.49 ± 0.9	29.26 ± 1.1	27.09 ± 1.4	<.001
FES-I	N/A	23.36 ± 2.9	20.41 ± 8.4	20.62 ± 4.7	.062
POMA balance score	16.00 ± 0.00	14.9 ± 1.6	15.01 ± 1.5	14.55 ± 0.9	.111
POMA gait score	12.00 ± 0.00	11.90 ± 0.3	12.00 ± 0.0	11.77 ± 0.4	<.001
POMA total score	28.00 ± 0.00	26.80 ± 1.9	27.01 ± 1.1	26.32 ± 0.6	.009
Preferred walking speed (m/s)	0.85 ± 0.00	0.63 ± 0.31	0.59 ± 0.4	0.57 ± 0.02	<.001
Number of falls	0.00 ± 0.00	1.40 ± 0.50	1.54 ± 0.77	1.00 ± 0.00	.010

Note. Values are means ± 1*SD*. MMSE = Mini-Mental State Examination; FES-I = fear of falling; POMA = Performance-Oriented Mobility Assessment.

Figure 1 — Experimental setup.

computer using an internal direct linear transformation algorithm. The data were grabbed, digitized, transformed, and smoothed using low-pass filter (Butterworth second-order forward and backward passes) with a cutoff frequency of 5 Hz. The ariel performance analysis system was shown to be valid and reliable, with a system mean point estimate error of less than 3.5 mm, 1.4 mm mean linear error, and 0.26° mean angular errors (Klein & DeHaven, 1995).

Data Processing

A reconstructed time series of 3D marker position data were used to extract kinematic features of gait. A semiautomatic graphical user interface was developed using Matlab software (MathWorks, Inc., Cambridge, MA) to detect initial contact (heel strike) timing for each leg (Figure 2a1 and 2a2). To calculate GA and PCI, we used only data from the ankle markers from both feet. The initial contact was determined by the time in which the ankle marker reached the maximal anterior value in the anterior posterior axis (*x*). Gait events

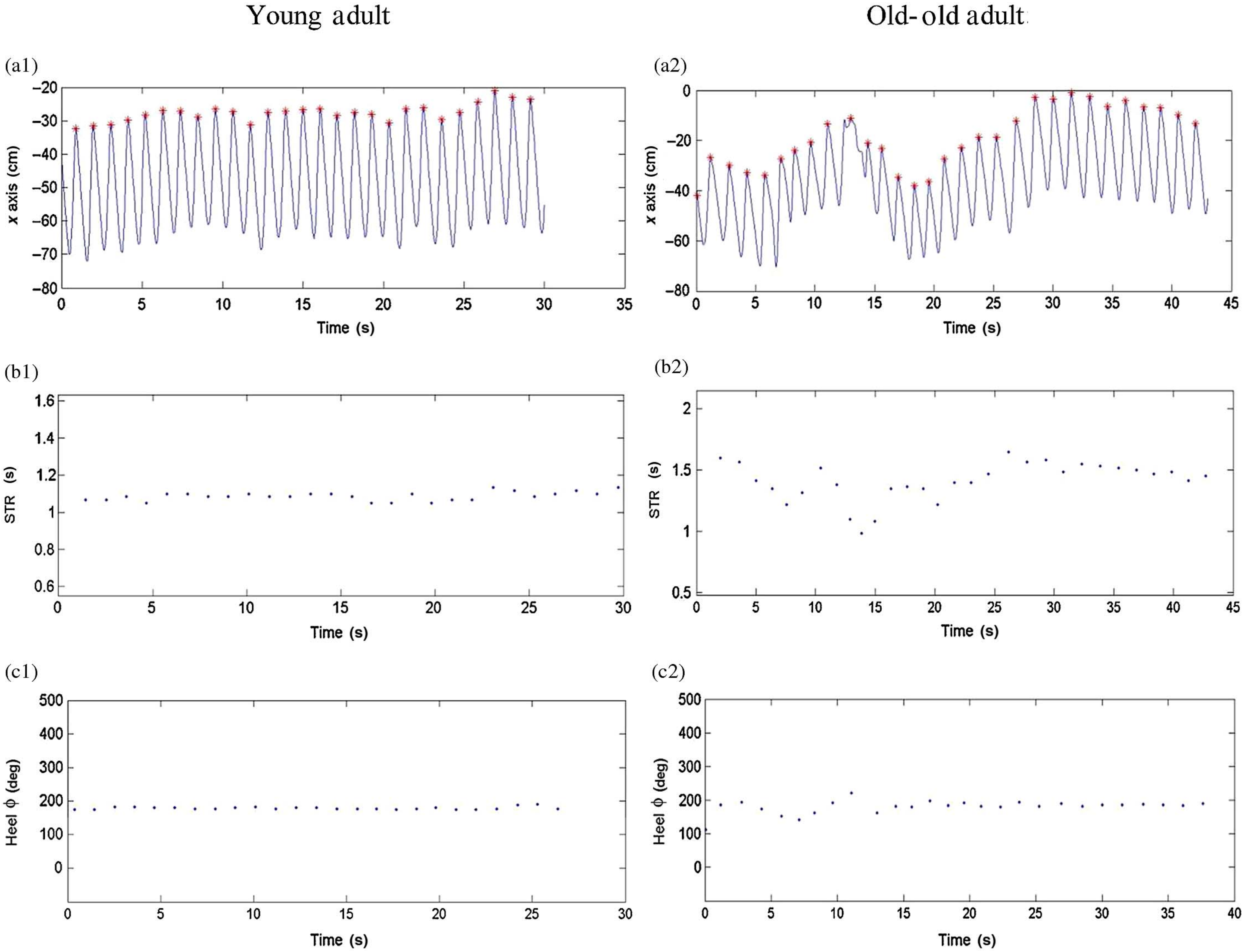

Figure 2 — Example of results from the graphical user interface for young subject and for old-old subject during the treadmill walking. Panels (a1) and (a2): Detection of heel strike. Panels (b1) and (b2): Time between two consecutive heel strikes of the left leg. Panels (c1) and (c2): Left–right stepping phase for each stride. *Note*. The step-to-step consistency and longer steps in the young's versus the old-old adults. *x* axis = anterior–posterior direction; STR = stride time; φ = phasing.

that were detected were the "heel strikes" on both legs. According to the sampling rate, there is inherent detection error of 8.3 ms. This error derives the temporal errors of the outcomes described later.

Based on the timing of this event, the following parameters were calculated:

Stride time—The time between two consecutive heel strikes of the same leg. For each walking condition, the mean stride time, *SD*, and CV were calculated for the left and right legs. As left and right stride times are highly correlated, we report here on the left leg (Figure 2b1 and 2b2).

Step time—The time lapse between the heel strike of one leg and a consecutive heel strike of the other leg. For each walking condition, the mean step time was calculated for the left and right legs (L_STP and R_STP, respectively). Errors in stride and step time determination are approximated to be 11.8 ms.

GA—The calculation of GA is performed according to the relationship (Yogev et al., 2007):

$$\text{GA} = 100 \times |\ln(\text{R\_STP}/\text{L\_STP})|.$$

The natural logarithm was applied to take into account the skewed nature of the data.

PCI—The coordination of left–right stepping was assessed using a recently described measure, PCI. First, we determined the left–right stepping phase φi (ideally $\varphi i = 180°$) for each stride (Figure 2c1 and 2c2). From each series of φi, the φi_CV% was calculated and the difference in percentage from the ideal φi, as the two components of the PCI. Lower PCI values reflect a more consistent and more accurate phase generation, while higher values indicate an impaired bilateral coordination of gait (Meijer et al., 2011; Plotnik et al., 2007; Plotnik, Giladi, & Hausdorff, 2008). A full description and derivation of the PCI metric is described in detail elsewhere (Plotnik et al., 2007).

Sample Size

The sample size estimation was made using the PS power and sample size calculations (version 3.0; Nashville, TN). Based on data presented elsewhere (Plotnik et al., 2007), the PCI was 2.47 ± 0.58 for young and 3.30 ± 0.67 for older adults. If the true difference between group means is 0.83 with *SD* of 0.6, a minimum of nine subjects in each group would be required to be able to reject the null hypothesis that the population means of the groups are equal with probability (power) 0.8. The Type I error probability associated with this test of this null hypothesis is 0.05.

Statistical Analysis

For statistical analysis, Predictive Analytics Software (PASW) statistics version 18.0 was used (IBM–version 18, Somers, NY). Mean values of the dependent variables were computed from the groups' data. The *SD* of each group was averaged from each subject's sum of strides at each speed condition (about 30 strides for each walking speed). To evaluate age-related differences in gait dynamics, analysis of variance for repeated measures was carried out to evaluate the main effects of walking speed (five walking speeds: 0.5, 0.6, 0.7, 0.8, and 0.9 m/s) and the effects of age (four between-groups factors: Y, YO, O, and OO). The interaction effect between walking speeds and age group was assessed as well. In cases where the model provided a statistically significant effect, a post hoc analysis (least significant difference) was carried out to contrast between the different age groups and the different walking speeds. The dependent variables were PCI, GA, stride time variability, and stride time. The level of statistical significance was set at $p = .05$. Seven subjects from O group felt unsafe during walking at the fast walking speeds (three during 0.8 m/s and four during 0.9 m/s); hence, their data were reported missing and excluded from the analysis. Gait parameters and subject's characteristics were not different between these seven subjects and the rest of the O group.

In a post hoc analysis, one-way analysis of variance was used to test for differences in mean values of the dependent variables between age groups at the subjects' average preferred treadmill walking speed (Y = 0.85 m/s, YO = 0.63 m/s, O = 0.59 m/s, and OO = 0.57 m/s). In cases of significance, a post hoc analysis was carried out to determine whether there were within-group significant differences in the dependent variables.

Results

The main effects of five different walking speeds, four age groups, and the interaction of walking speed and age are reported in Table 2. There were significant main effects of walking speeds on PCI ($p = .01$) and stride time ($p < .001$). In addition, there were significant main effects of age on stride time ($p < .001$), while PCI was not significant ($p = .066$), with no significant interaction between walking speed and age group ($p = .386$). There were no significant main effects of walking speed and age on either GA or stride time variability without significant interaction between walking speed and age group (Table 2).

Results in Table 3 relate to the preferred treadmill walking speed and show a significant difference in stride time variability ($p < .001$) between the age groups, while PCI was almost significant ($p = .073$). There were no significant differences in GA and stride time ($p = .930$ and $p = .161$, respectively).

Phase Coordination Index

A significant main effect of walking speed was found for PCI, but only borderline for age ($p = .066$). Although there was no significant interaction for treadmills walking speeds and age groups, the Y consistently showed smaller PCI values than the YO, O, and OO groups. Post hoc analysis for speed conditions revealed that PCI was significantly lower in treadmill walking speed of 0.5 m/s compared with 0.6 m/s. However, at the speed of 0.6 m/s, PCI was significantly higher compared with 0.7 and 0.8 m/s. Post hoc analysis for age groups revealed that Y had a significantly lower values of PCI (i.e., more consistent and more accurate bilateral coordination of gait) only when compared with the OO ($p = .009$; Figure 3). In addition, post hoc analysis revealed significant differences between Y and OO during walking in their preferred walking speed (Table 3).

Gait Asymmetry

There was neither a main effect of walking speeds or age, nor an interaction of walking speed with age. In addition, there were no differences in GA when comparing all age groups while walking at their preferred treadmills walking speed.

Stride Time Variability

No significant main effects of walking speeds or age, or interactions, were found for stride time variability. However, a comparison of the subjects' preferred treadmill walking speed revealed

Table 2 Comparison Between the Four Age Groups at the Different Speeds of PCI, GA, Stride Time Variability, and Stride Time, Based on Repeated-Measures ANOVA (5 Speeds × 4 Groups)

							ANOVA		
Variables	**Age group**	**0.5 m/s**	**0.6 m/s**	**0.7 m/s**	**0.8 m/s**	**0.9 m/s**	**Speed**	**Group**	**Speed × Group**
PCI (%)	Young	7.25 ± 1.65	7.44 ± 2.07	6.57 ± 2.24	7.46 ± 2.63	7.65 ± 3.17	$F = 3.881$	$F = 2.596$	$F = 1.077$
	Young-old	8.69 ± 5.93	11.37 ± 4.48	9.04 ± 5.46	9.87 ± 4.90	8.60 ± 3.45	$p = .010$	$p = .066$	$p = .386$
	Old	7.46 ± 3.89	9.31 ± 2.81	8.85 ± 2.83	9.32 ± 4.05	9.37 ± 3.88			
	Old-old	11.11 ± 3.65	13.77 ± 7.15	10.21 ± 3.51	9.98 ± 4.28	12.15 ± 7.61			
GA (%)	Young	6.11 ± 2.39	5.92 ± 3.94	6.14 ± 3.04	5.27 ± 3.89	7.41 ± 5.42	$F = 0.366$	$F = 1.336$	$F = 0.633$
	Young-old	6.06 ± 6.09	5.75 ± 4.93	6.25 ± 6.19	5.67 ± 5.99	3.68 ± 2.97	$p = .832$	$p = .276$	$p = .811$
	Old	3.67 ± 2.96	6.04 ± 5.60	6.03 ± 5.31	5.38 ± 4.77	7.39 ± 8.07			
	Old-old	10.78 ± 5.04	9.81 ± 3.94	9.28 ± 2.85	8.46 ± 3.93	9.41 ± 5.18			
Stride time variability (CV%)	Young	4.79 ± 2.83	3.38 ± 0.65	3.06 ± 1.25	2.63 ± 0.62	2.23 ± 0.64	$F = 1.593$	$F = 1.934$	$F = 1.183$
	Young-old	3.84 ± 2.39	4.47 ± 1.41	4.28 ± 1.53	4.58 ± 1.45	5.01 ± 2.66	$p = .193$	$p = .138$	$p = .302$
	Old	4.81 ± 4.23	4.60 ± 2.43	3.85 ± 1.58	3.66 ± 1.59	4.41 ± 3.32			
	Old-old	5.61 ± 3.34	5.33 ± 2.43	4.21 ± 1.40	5.53 ± 4.97	7.46 ± 6.94			
Stride time (s)	Young	1.44 ± 0.21	1.40 ± 0.17	1.33 ± 0.14	1.25 ± 0.10	1.21 ± 0.09	$F = 17.880$	$F = 8.500$	$F = 1.755$
	Young-old	1.04 ± 0.53	1.18 ± 0.14	1.14 ± 0.12	1.09 ± 0.12	1.06 ± 0.10	$p < .001$	$p < .001$	$p = .063$
	Old	1.03 ± 0.42	1.14 ± 0.13	1.12 ± 0.12	1.09 ± 0.11	1.06 ± 0.10			
	Old-old	1.25 ± 0.15	1.23 ± 0.17	1.21 ± 0.16	1.18 ± 0.13	1.14 ± 0.12			

Note. Values are means ± 1*SD*. ANOVA = analysis of variance; CV = coefficient of variance; PCI = phase coordination index; GA = gait asymmetry.

Table 3 Comparison Between the Four Age Groups at the Preferred Treadmill Walking Speed (One-Way ANOVA)

Variables	Age group	Preferred speed (m/s)	ANOVA-Group	Post hoc
PCI (%)	Young	7.30 ± 2.83	$F = 2.459$ $p = .073$	Young vs. old-old ($p = .011$)
	Young-old	10.44 ± 5.51		
	Old	10.06 ± 4.02		
	Old-old	12.38 ± 6.17		
GA (%)	Young	7.41 ± 5.42	$F = 0.149$ $p = .930$	Not significant
	Young-old	7.19 ± 5.96		
	Old	6.99 ± 6.85		
	Old-old	8.56 ± 4.50		
Stride time variability (%)	Young	2.23 ± 0.64	$F = 8.483$ $p < .001$	Young vs. young-old ($p < .001$); Young vs. old ($p < .001$) Young vs. old-old ($p < .001$)
	Young-old	4.90 ± 1.75		
	Old	4.24 ± 1.55		
	Old-old	5.03 ± 2.03		
Stride time (s)	Young	1.21 ± 0.09	$F = 1.788$ $p = .161$	Not significant
	Young-old	1.15 ± 0.11		
	Old	1.13 ± 0.12		
	Old-old	1.20 ± 0.13		

Note. Values are means ± 1*SD*. ANOVA = analysis of variance; PCI = phase coordination index; GA = gait asymmetry.

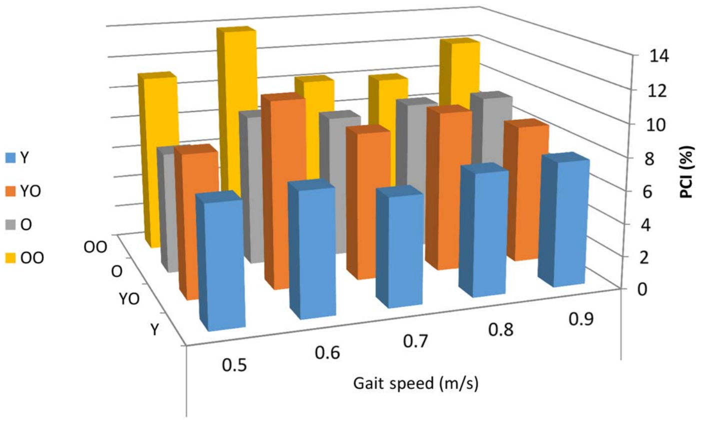

Figure 3 — Results of phase coordination index. Significant main effect of walking speed was found for PCI, but not for age ($p = .066$). The Y consistently showed smaller PCI values than the YO, O, and OO groups. Y had significant lower values of PCI only than the OO. PCI = phase coordination index; Y = young; YO = young-old; O = old; OO = old-old.

significant differences (Table 3). The post hoc analysis showed that Y had significantly lower values of stride time variability (i.e., more rhythmic) than YO, O, and OO, with no differences between the older groups.

Stride Time

The stride time had a significant main effect of walking speeds and age, but only a trend to significant interaction with age groups ($p = .063$; Table 2). Post hoc analysis for walking speed conditions showed significant differences between all walking speed conditions. Post hoc analysis for age groups revealed that Y had significant longer stride time than YO and O, but without significant difference compared with OO. There were no age-related differences when walking at the preferred treadmills walking speed.

Discussion

This study partially supports our hypotheses: (a) the OO adults presented higher PCI compared with young adults, without positive interaction with walking speed; (b) PCI significantly decreased due to increasing walking speed, without significant main effect of age or interaction with walking speed; (c) the OO adults did not show higher GA. GA did not change due to changes in treadmills walking speed or age; (d) the OO adults did not significantly increase stride time variability when treadmill walking speed was controlled; and (e) stride time variability increased with age only at the preferred treadmill walking speed. Only changes of walking speed and not age led to significant changes in PCI and not in GA and gait variability; thus, the key finding of this study is that PCI is the most prominent order parameter and gait speed is the control parameter.

Based on our results, gait speed is the main determining attractor for bilateral coordination of gait and is superior to age as an attractor for a left–right antiphase stepping pattern. But still the post hoc analysis showed significantly higher PCI values in the OO group compared with Y. The lack of an interaction of age and treadmills walking speed for timing parameters such as PCI, GA, and stride time variability reinforces the finding that cross-age coordination parameters react similarly to the change of gait speed.

Our results differ from earlier studies that showed a significant increase in GA and PCI in older adults (Plotnik et al., 2007; Yogev et al., 2007), who were younger than the YO group of this study. These differences may result from the fact that those studies (Plotnik et al., 2007; Yogev et al., 2007) tested their subjects at overground walking, which is less motor demanding than maintaining speed at a dictated level. For example, PCI values for young adults were ~2.4%, and in 69 years older adults, they were ~3.3% (the ratio is ~1.3; Plotnik et al., 2007). Table 3 shows that PCI values between the present cohorts of Y and YO have a similar ratio (~1.4). Gait coordination variability is an intrinsic element of motor behavior for gait and refers to the ability to reorganize walking movements in response to external demands such as treadmill walking. As Chiu, Chang, and Chou (2015) showed that when walking at a similar speed, the interjoint coordination patterns are similar between treadmill and overground conditions.

It appears that neural mechanisms governing gait changed the internal variability of the stride times for each subject (otherwise, the stride time variability at the different walking speeds were with the same difference as at preferred walking speed) to keep bilateral coordination of gait as uniform as possible across walking speeds. However, the differences seen in PCI values at different walking speeds are due to limited compensation reserves. These results are in agreement with those of Sadeghi (2003), who showed that total behavior of the limbs is symmetrical but recognized compensations from the knees and hips that had local asymmetry.

In addition, our results showed that stride time variability values were significantly different between age groups only at the preferred treadmill walking speed. In fact, as can be inferred from Tables 2 and 3, avoiding the subject from the preferred walking speed and further moving away from their preferred walking speed resulted in increased stride time variability. Similarly, Jordan et al. (2007) showed a distinct U-shaped pattern of change in the strength of the correlation of stride time variability with speed, with the minima of the curve falling between 100% and 110% of the preferred walking speed.

PCI and GA differences between the OO and the Y are the largest, although these differences are significant only for the PCI. Based on these differences, we claim that the PCI is a more sensitive variable for evaluating gait coordination than GA. In independent older adults who are able to maintain symmetric motor activation of their legs while walking, the PCI might indicate the onset of gait deterioration, as the significant differences between Y and OO might suggest.

The differences in PCI between Y and OO only suggest that for independent older adults, neuronal circuits controlling bilateral coordination of gait (e.g., central pattern generators) in the spinal cord (Duysens & Van de Crommert, 1998) and the neural linkages between the spinal cord and the brain (Arya & Pandian, 2014)] enable accurate and consist antiphased left–right stepping until a very old age.

Human coordination changes similarly during different gait speeds across all ages. However, deterioration in consistency and accuracy of gait coordination occur especially during slow walking at a very old age. Based on our results, it seems that treadmill training with manipulation of walking speed might be beneficial for coordination maintenance or even improvement beyond the general fitness gain.

This study has several limitations. First, the data came from a small sample of relatively healthy and independent older adults; these results cannot be generalized to extremely weak or institutionalized older adults who cannot walk independently on a treadmill. Further study should involve frail older adults. Second, the question of whether the characteristics of gait—PCI, GA, and stride time variability—during treadmill walking provide a good estimate of their characteristics during overground gait may be a drawback of our protocol. One difference between treadmill and overground walking is the absence of visual flow on the treadmill, which also occurs in overground walking in a large featureless space, where visual flow is minimal. Another difference is that during treadmill walking, the ground is moving under the feet, thus push off leg power is less necessary. Studies indicate that vertical trunk translation is larger during treadmill walking than overground walking. However, after brief training, the differences between treadmill and overground walking became insignificant (Murray, Spurr, Sepic, Gardner, & Mollinger, 1985). Chiu et al. (2015) showed that when walking at a similar speed, the interjoint coordination patterns are similar between treadmill and overground conditions. This suggests that the characteristics of normal locomotion can be adequately studied on a treadmill. Furthermore, Moe-Nilssen and Helbostad (2005) suggested that when differences in gait parameters during overground walking between populations demonstrate different walking speeds, the results may be biased. Thus, using treadmill walking at different walking speeds may lead to the ability to compare age-related changes in coordination patterns that are not related to a difference in gait speed.

The results of this study suggest that walking speed is an important independent variable in the evaluation of older adults' gait and can be used as a basis for the classification of gait deficits.

Conclusions

This study explicitly shows that bilateral coordination of gait is influenced by gait speed and significantly deteriorates at a very old age (aged 85 years and older). These data suggest the importance of distinguishing between different groups within an aging population. In addition, the data suggest that mechanisms governing coordination react similarly to the change of gait speed in independent older adults across all ages.

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