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The Effect of Walking Speed on Gait Variability in Healthy Young, Middle-aged and Elderly Individuals

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Abstract

Previous research with healthy young adults has suggested that the temporal structure of gait variability is not random but shows self-similarity that is dependent on speed. Specifically, the strength of the long-range correlation of stride intervals follows a quadratic relationship with the minimum values at the respective preferred walking speed (PWS). The purpose of this study was to investigate if this relationship is affected by increasing age. Ten healthy young, seven healthy, middle-aged and seven healthy, elderly adults completed five-minute walking trials at 80%, 90%, 100%, 110% and 120% of their PWS on a treadmill. We investigated the temporal structure of gait variability by using detrended fluctuation analysis. In addition, we computed the Coefficient of Variation (CV) to identify effects on amount of gait variability. Our results revealed a significant quadratic relationship between the temporal structure of gait variability and speed for all groups extending the previously reported existence of such a relationship in healthy young adults to older individuals. However, only significant negative linear relationships were found between amount of variability and speed providing support that this relationship is not quadratic but linear across individuals of different ages. In addition, we found that the examination of the temporal structure of gait variability is more sensitive in differentiating middle-age and younger individuals. If middle-age is where the aging process starts, then measures of the temporal structure of gait variability are essential as prognostic and diagnostic tools of aging.

Keywords: walking speed, gait variability, age

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1 Introduction

Previous research has shown that gait variability and speed present a quadratic, i.e. U-shaped, relationship in healthy young adults (Jordan, Challis, & Newell, 2007; Sekiya, Nagasaki, Ito, & Furuna, 1997). Specifically, Sekiya et al. (1997) utilized a measure of the amount of variability, the coefficient of variation (CV), and found that the CV of step length and step rate exhibited a local minimum at the preferred walking speed in young adults. The authors suggested that walking at one's preferred walking speed (PWS) demonstrates an optimal variability not only in terms of temporal, but also of spatial parameters. Furthermore, Jordan et al. (2007) used detrended fluctuation analysis (DFA) to investigate the influence of walking speed on the temporal structure of gait variability in young adults (Jordan et al., 2007). The a-value returned by the DFA algorithm could provide information about the presence of long range correlations from one stride to the next during walking. Jordan et al found that the a-values of the stride interval, stride length, step interval, step length and impulse revealed a quadratic relationship with speed. The minimum a-value was located between 100% and 110% of PWS. The

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authors suggested that the reduced strength of long range correlations at preferred locomotion speeds is reflective of enhanced stability and adaptability at these speeds. Specifically, the reduction in a-values at PWS could be related with improved stability associated with walking at their self-selected resonance frequency. It has been shown that rhythmic gait at resonance improves cycle-to-cycle reproducibility and stability (Jordan, Challis, & Newell, 2006).

In the present study, we wanted to extend the above presented work and investigated how aging affects these relationships. Specifically, we wanted to identify if as we age the CV and the a-values of the stride intervals during walking reveal similar relationships between gait variability and speed. For this purpose, we recruited a young group (20-40 years old), a middle-aged group (40-60 years old) and an elderly group (over 60 years old). The use of a middle-aged group was motivated by previous research work by Agrawal, Platz and Niparko (2009). These authors suggested that aging starts much earlier with subtle but noticeable balance and gait related disturbances evident in individuals aged 40-49. These subtle disturbances eventually lead to falls as aging occurs and the authors identified that 15% of US adults, approximately 28 million people aged 40-49, experience such problems (Agrawal et al., 2009).

2 Methodology

Twenty-four healthy individuals (seven elderly of 70±10 years old; seven middle-aged of 50±5 years old and ten young adults of 27±4 years old,) participated in this study. All participants were screened and did not have a history of cardiovascular, neurological, and/or musculoskeletal disorders. Prior to participation all subjects provided consent according to the Institutional Review Board guidelines of our University.

Three dimensional marker position data (3D Investigator Motion Capture System, Northern Digital Inc., Waterloo, Ontario, Canada) was recorded at 100 Hz (First Principles Software, Northern Digital Inc., Waterloo, Ontario, Canada) while subjects walked on a treadmill (Bertec Corporation, Columbus, Ohio). The motion capture system collected data in real time by way of flashing infrared smart markers. The marker positions were calibrated to two camera tubes that contained three position sensors each. The markers were arranged and secured into clusters of three creating a rigid body. Rigid bodies were secured to the lateral side of each foot, allowing four anatomical landmarks to be identified from each foot. These four landmarks were the toe, heel, first and fifth metatarsal head. The position data were recorded in real-time along with the rigid body position data for both feet.

Each subject walked on the treadmill at increasing speeds until they indicated that the current speed was comfortable. The speed was then increased by 0.10 m/s and they were asked to walk at the increased speed for one minute. If they indicated that this speed was still comfortable, the speed was then increased again. This was done until the subject indicated that the speed was too fast. In that case, their speed was brought back to the last comfortably indicated speed. They walked at this speed (preferred walking speed) for five minutes to ensure that this speed was in fact, the most comfortable. This process was repeated until we were certain that their preferred walking speed had been found. Participants then completed seven-minute trials at each of the following percentages of their preferred walking speed: 80%, 90%, 100%, 110% and 120%. These are the typical percentages used in the literature (Jordan et al., 2006, 2007; Kang & Dingwell, 2008). The foot position data was recorded between minutes 2-7 of each condition (five minutes of data collected). This ensured that the participant was

allowed to acclimate to each speed. The five speeds were presented randomly and participants were given a minimum of two minutes to recover between trials.

The stride interval was defined by determining the time between two consecutive heel contacts of the ipsilateral leg using the heel marker position data via custom software (MatLab, Mathworks, Inc., Natick, MA). This parameter was selected due to its commonality among studies and it has been previously used with the DFA algorithm (Jordan et al., 2006, 2007 ; Hausdorff, Lowenthal, Herman, Gruendlinger, Peretz, & Giladi, 2007; Hausdorff, Mitchell, Firtion, Peng, Cudokowicz, Wei, & Goldberger, 1996; Hausdorff, Peng, Ladin, Wei, & Goldberger, 1995). Two hundred consecutive strides were used for data analysis from each trial based on the maximum number of strides from the slowest walking elderly individual.

All trials were then cut to this length. The CV and DFA of the stride interval were calculated from the time series of each trial. The CV was measured as the ratio of the standard deviation to the mean and provided a measure of the amount of gait variability. The DFA was used to determine the strength of long-range correlation over time and provided a measure of the temporal structure of variability.

The DFA is a modified random-walk analysis that makes use of a long-range correlated time series. The long-range correlation can be mapped to self-similar calculations through simple integration. First, the time series is integrated and then divided into window sizes of length n. A least squares fit line is fit to the data in each window, and data is detrended by subtracting the integrated time series from the least squares fit line. The root mean square is then calculated for each window and summed for the entire time series, F(n). The process is repeated with smaller and smaller n window sizes. Finally, the log F(n) is plotted against the log n (the root mean square versus the window sizes). The slope of this plot is the reported ?-value. If the a-value is greater than 0.5, the long-range correlation is positively persistent. Meaning that increases are followed by increases and decreases are followed by decreases. Whereas if the a-value is smaller than 0.5, the long-range correlation is anti-persistent, meaning increases are followed by decreases and vice versa. If the a-value is greater than 1, the signal is regarded as Brown noise (Jordan et al., 2007).The range of window sizes of the DFA selected in current study was from n1 = 4 to nm = N/4, where N is the number of stride intervals (Jordan et al., 2006). This specific window size of the DFA was chosen as it provides a statically robust measure of stride-interval correlations that are independent of finite size effects (length of data) (Peng, Buldyrev, Goldberger, Havlin, Mantegna, Simons, & Stanley, 1995).

To identify the relationship between each of the dependent variables (CV and a-values) with percentage of preferred walking speed, trend analyses were utilized (Keppel, Saufley, & Tokunaga, 1992). Two-way repeated measures ANOVAs (3 groups X 5 speeds) were also used to investigate the effects of age and speed on the CV and the a-values of the stride interval time series. Post hoc analysis was performed using the Tukey test when necessary. Statistical analysis was completed in SPSS 16.0 (IBM Corporation, Armond, NY). The level of significance was set at 0.05.

3 Results

Significant quadratic relationships were found between the a-values of the stride interval and the percentage of preferred walking speed in the young (F=11.204, p=0.002), the

middle-aged (F=11.326, p=0.002) and the elderly (F=12.777, p<0.001) groups (Table 1, Figure 1). On the contrary, the corresponding linear relationships were not found to be significant for the young (F=0.68, p=0.414) and the middle-aged group (F=0.991, p=0.328). There was only a significant linear relationship for the elderly group (F=5.468, p=0.026) (Table 1). In addition, significant age (F=7.835, p=0.003) and speed (F=21.222, p<0.001) main effects were found for the a-values of the stride interval time series (Table 2). There was a significant interaction (F=3.532, p=0.001). The post-hoc analysis showed that the a-value in the 80% preferred walking speed condition was significantly larger than the 110% preferred walking speed condition (p=0.018) in the young group. The post-hoc analysis also showed that the a-value in the 80% preferred walking speed condition was significantly larger than the 100% preferred walking speed condition (p=0.004) in the middle-age group. For the elderly group, the post-hoc analysis showed that a-value in the 80% preferred walking speed condition was significantly larger than the 90% (p=0.017), the 100% (p<0.001), and the 110% (p=0.007) preferred walking speed conditions. There were no significant differences for the a-value among the different speeds in the young adults. The post hoc analysis also showed that the a-value in 100% preferred walking speed condition was significant larger in the young adults than the middle-age adults (p=0.025) and the elderly adults (p=0.048). There was no significant difference in the a-value of the 100% preferred walking speed between the middle-age and the elderly adults (p=0.955) (Table 2).

No significant quadratic relationships were found between the CV of the stride interval time series and the percentage of preferred walking speed in any of the groups (young (F=0.013, p=0.91), middle-aged (F =0.056, p=0.816), elderly (F=0.04, p=0.844)). However, the linear relationships between the CV of stride interval and the percentage of preferred walking speed were found to be significant in all groups (the young (F=12.436, p=0.001) middle-aged (F=5.214, p=0.033), elderly (F=7.313, p=0.014)) (Table 1, Figure 2). A significant main effect was found for age (F=4.97, p=0.02) and speed (F=27.047, p<0.001). The post-hoc analysis showed that the CV in the 80% preferred walking speed was significant larger in the elderly adults as compared with the young adults (p=0.013) and compared with the middle-age group (p=0.03).

Table 1. The F-values and P-values from the linear and quadratic trend analyses of the coefficient of variation (CV) and the α -values of the stride interval time series for the young (Y), the middle (M) and the elderly (E) groups from the five different walking speeds. Degrees of freedom were 1 and 30 for all analyses. It can be clearly seen that the quadratic relationships are stronger for the α-values in both groups that the linear, while the opposite is the case with CV.

	F-values (P-values)	
Relationships	Linear	Quadratic
α-values (Y)	0.68 (0.414)	11.204 (0.002)
α-values (M)	0.991(0.328)	11.326 (0.002)
α-values (E)	5.468 (0.026)	37.502 (< 0.0001)
CV (Y)	12.436 (0.001)	0.013 (0.91)
CV (M)	5.214 (0.033)	0.056 (0.816)
CV (E)	7.373(0.014)	0.04 (0.844)

Table 2. Group means and standard deviations of the α-values of the stride interval and the coefficient of variation (CV), expressed as a percentage, of the young (Y), the middle age (M) and the elderly (E) group for the five different walking speeds (% of preferred walking speed).

	80% of PWS	90% of PWS	100% of PWS	110% of PWS	120% of PWS	Main effect of age	Main effect of speed	Interaction
α-value (Y)	0.86 ± 0.11	0.77 ± 0.07	0.76 ± 0.07	0.75 ± 0.09	0.85 ± 0.08	F = 7.835, p = 0.03	F= 21.222, p < 0.001	F = 3.532, p = 0.001
α-value (M)	0.96 ± 0.10	0.81 ± 0.13	0.64 ± 0.10	0.84 ± 0.19	0.86 ± 0.12			
α-value (E)	1.13 ± 0.11	0.92 ± 0.14	0.69 ± 0.08	0.90 ± 0.07	0.98 ± 0.17			
CV (Y) (%)	3.08 ± 1.24	2.33 ± 0.88	2.02 ± 0.72	1.92 ± 0.74	1.65 ± 0.44			
CV (M) (%)	2.78 ± 1.15	2.32 ± 0.46	1.92 ± 0.51	1.90 ± 0.73	1.70 ± 0.4	F = 4.97, p = 0.02	F = 27.047, p < 0.001	F = 2.145, p = 0.043
CV (E) (%)	3.75 ± 1.49	3.57 ± 1.41	2.93 ± 1.49	2.43 ± 0.99	2.29 ± 1.00			

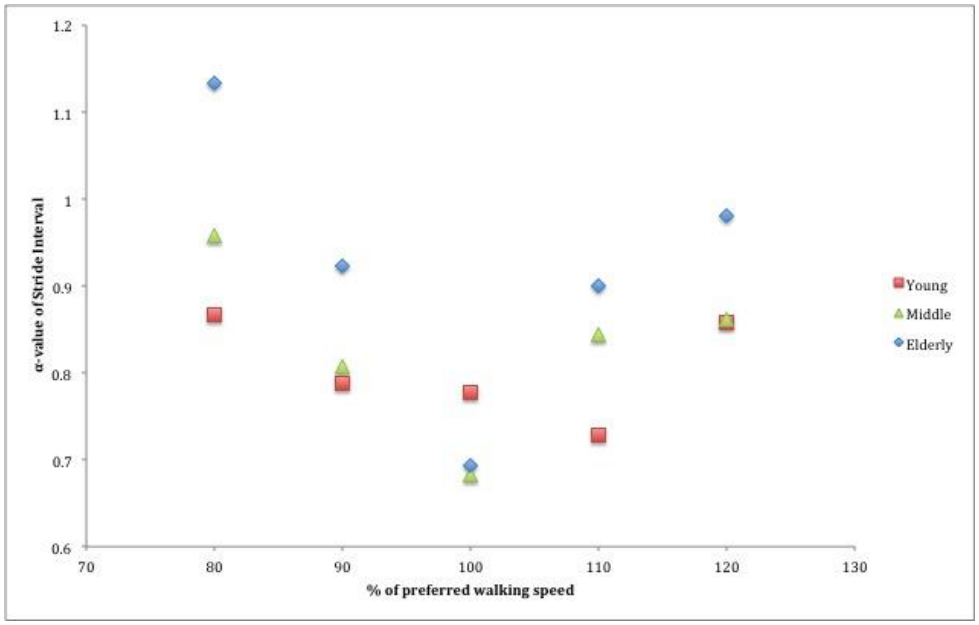


Figure 1. Group means of the α-values of the stride interval time series from the five different walking conditions: (80%, 90%, 100%, 110% and 120% of preferred walking speed).

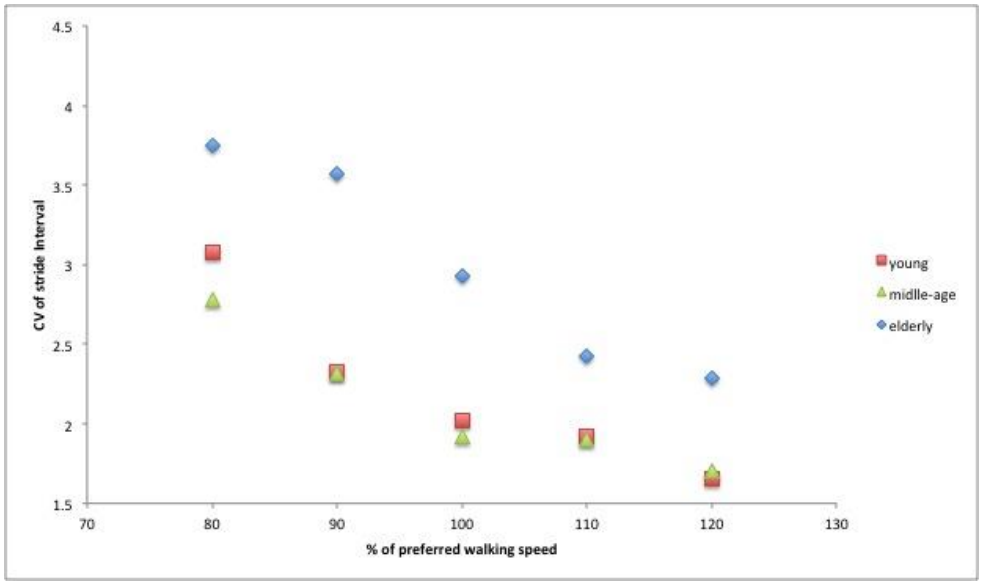


Figure 2. Group means of the α-values of the stride interval time series from the five different walking conditions: (80%, 90%, 100%, 110% and 120% of preferred walking speed).

4 Discussion and conclusions

In the present study, we extended the previous works by Jordan et al., (2007) and investigated how aging affects the long-range correlation among different speeds. Further, we wanted to identify if aging results in similar patterns in measures of the amount and the temporal structure of gait variability among different walking speeds. For this purpose, we recruited young (20-40 years old), middle-aged (40-60 years old), and elderly (above 60 years old) healthy individuals. We found that gait variability demonstrated different patterns in the amount and the temporal structure of the stride interval measure among different speeds. A strong quadratic relationship existed in all age groups between speed and temporal structure of gait variability. However, this was not the case regarding the amount of gait variability where a linear relationship was evident. Importantly, we also found that the temporal structure of gait variability was more sensitive to aging than the amount of gait variability in terms of the stride interval.

It has been suggested that human walking is fractal-like (Hausdorff et al., 1995). The stride-to-stride fluctuations of human walking are not simply random but also existing long-range correlations, where a given stride interval is related to other stride intervals that occur much later. The presence of long-range correlation and fractal-like scaling of the stride interval in healthy young adults was confirmed in preferred, slow, and fast walking speed (Jordan et al., 2007). Previous research also indicated relative smaller a-values at the preferred walking speed (PWS) in healthy young individuals because PWS was more adaptable than other walking speeds due to less constraint walking (Jordan et al., 2007). Our results revealed that similar minima of a-values at PWS are also observed in both middle-aged and elderly individuals (Figure 1). Why the relative minimum of the a-value is located at PWS in all three age groups? It has suggested that humans tend to walk at PWS in order to use a minimum amount of energy (Brisswalter & Mottet, 1996). Either increasing or decreasing walking speed causes higher energy consumption than walking at PWS. Based on dynamical system theory (Brisswalter &

Mottet, 1996) the PWS reflects a stable attractor state of the motor system. Increasing or decreasing the walking speed causes the system to depart from this stable state and to move away from the attractor resulting in instability. Thus, we speculate that humans, regardless their ages, always select stable, low energy consumption, adaptable, and fractal-like walking speeds as their PWS. When walking faster or slower, the higher energy consumption might be required to compensate for the loss of stability.

Interestingly, our results demonstrated that the highest a-values (a = 1.2) was exhibited in the elderly group during the slowest walking condition (80% of PWS). Similar a-values were found in the heartbeat interval of healthy elderly individuals (a ~= 1.3) and patients with heart failure (a ~= 1.5) (Goldberger, Amaral, Hausdorff, Ivanov, Peng, & Stanle, 2002). This indicates that such an a-value level could be associated with the aging process or pathological disorders. Goldberger et al., (2002) showed that the alternations of scaling behavior from fractal-like to Brownian motion (a-values ~= 1.2) due to aging might be associated with the loss of integrated physiologic responsiveness, which means that the complexity of system might be deteriorated. The optimal complexity of system should contain fractal-like motion (e.g. not too random and not too regular motion). It is known that during the normal aging process, the function of the motor unit begin to decrease the age of 40 (Faulkner, Larkin, Clafin, & Brooks, (2007). Thus, healthy elderly adults may need to recruit a larger number of motor units to compensate with the neuromuscular demands of the slowest walking condition. Thus, the complexity of the system is reduced because of a larger numbers of motor units that are activated in a random and non-organized fashion to achieve this motion.

Comparing the a-values at PWS in the present study with those from Hausdorff et al., (1995), we found that our results from both middle-aged and elderly groups were similar to their elderly group (0.69 ± 0.09) while they were lower than our young individuals (Jordan, et al., 2007). They suggested that the loss of long-range correlation (lower a-value) from stride-to-stride could be due to the deterioration of central processing mechanisms resulting from aging or central nervous system disease(s) (Hausdorff et al., 2007). Since the a-values of both the middle-aged and the elderly groups in this study are similar to the elderly group in the Hausdorff et al's study (2007), it is possible that the deterioration of central processing mechanisms might begin as early as middle-age. In fact, there is evidence that the vestibular system declines earlier than the other two sensory systems (visual and somatosensory system) that are used for maintaining balance, starting at approximately the age of 40 years (Lockhart, Spaulding, & Park, 2007).

Our results also showed that the relationship between amount of variability and walking speed is not exactly the same as it has been previously reported. However previous reports are also inconsistent since three studies found such a relationship to be negatively linear (Bollens, Crevecoeur, Detrembleur, Gauillery, & Lejeune, 2012; Jordan et al., 2007; Kang & Dingwell, 2008), whereas another study found a quadratic relationship (Sekiya et al., 1997). Our results supported the negative linear relationship between amount of variability and walking speed in all three age groups. We speculate that the number of strides could lead to different results. Instead of walking on the treadmill (Jordan et al., 2007; Kang & Dingwell, 2008), Sekiya et al., (1997) asked subjects to walk on a level walkway (0.6m x 16m). The length of walkway limited the number of strides. Fewer strides might generate larger variation. In addition, we found

that the amount of variability in the elderly group was significantly higher than the other two groups only in the slow walking condition (Bollens et al., 2012). The increased amount of variability in the slow walking condition could be inferred as gait becoming more unstable in the elderly individuals. However, amount of variability failed to yield differences between middle-aged and young groups. We speculate that measures of the amount of variability might not be as sensitive to aging effects as measures of the temporal structure of variability. Other studies have also shown no significant differences in the same measure of the amount of variability between elderly and young adults at PWS (Hausdorff et al., 1996; Kang &Dingwell, 2008).

One potential limitation of this study was that subjects walked on a motorized treadmill, which may artificially reduce variability as compared to overground walking. In addition, lack of optic flow during walking on treadmill might cause alternations in gait variability (Dingwell, Cusumano, Cavanagh, & Sternad, 2001). Therefore, a self-control speed treadmill could be utilized and the optic flow could be presented via a virtual reality setting to further understand the relationship between gait variability and walking speed across different age groups.

In conclusion, our results support a quadratic relationship between the temporal structure of gait variability and speed across different ages, while supports a negative linear relationship between amount of gait variability and speed across different ages. Furthermore, our results have demonstrated that the examination of the temporal structure of gait variability may be more sensitive in identifying differences due to the aging process.).

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