Published in final edited form as:

J Aging Phys Act. 2018 October 01; 26(4): 577–582. doi:10.1123/japa.2017-0225.

Differential Gait Patterns by History of Falls and Knee Pain Status in Healthy Older Adults: Results From the Baltimore Longitudinal Study of Aging

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Abstract

Consideration of knee pain can be crucial for identifying fall-related gait patterns. While walking, gait parameters at usual speed were examined in persons with different falls and knee pain status. A total of 439 adults aged 60–92 years participated in this study. Persons with a history of falls had a wider stride width ($p = .036$) and longer double support time ($p = .034$) than nonfallers. In the absence of knee pain, fallers had longer double support time than nonfallers ($p = .012$), but no differences in double support time by history of falls were observed in participants with knee pain. With slower gait speed, fallers with knee pain have narrower stride width and larger hip range of motion ($p = .027$ and $p = .001$, respectively). Results suggest the importance of considering knee pain in fall studies for better understanding the fall-related differential gait mechanisms and for designing fall prevention intervention strategies.

Keywords

double support time; fall-related gait patterns; stride width

About 20–30% of persons who fall suffer moderate to severe injuries, such as lacerations, fractures, and head trauma (Alexander, Rivara, & Wolf, 1992; Sterling, O'Connor, & Bonadies, 2001). Falls among older adults can be even more devastating considering both the higher frequency of falls and more serious injuries that occur. Although prior studies have identified signature gait characteristics of individuals predisposed to falling (Ko et al., 2007; Lord, Lloyd, & Li, 1996; Moreland, Richardson, Goldsmith, & Clase, 2004; Verghese,

Holtzer, Lipton, & Wang, 2009), considerations of whether or how other factors affect gait characteristics among fallers are rare.

Chronic musculoskeletal pain in older adults is associated with greater occurrence of falls (Leveille et al., 2009). Specifically, knee pain, which affects approximately a quarter of older adults (McAlindon, Snow, Cooper, & Dieppe, 1992; O'Reilly, Muir, & Doherty, 1996) and increases with age (Peat, McCarney, & Croft, 2001), was associated with slower gait speed, longer double support time, and smaller range of motion (ROM) in hip and knee joints while walking (Bindawas, 2016; Kitayuguchi et al., 2015; Ko, Simonsick, & Ferrucci, 2015; Tas et al., 2014). Knee pain during walking is also related with older age, overweight, abnormal gait patterns, and knee osteoarthritis (Chang et al., 2016; Grodzinsky, Levenston, Jin, & Frank, 2000; Miranda, Viikari-Juntura, Martikainen, & Riihimäki, 2002). Considering the high prevalence of knee pain in older adults and its association with slower gait speed, knee pain could be an important additional factor in fall-related gait patterns of older adults. If fall-related gait patterns differ in the presence versus the absence of knee pain, examining how knee pain may alter risk of falls could lead to more efficient and individualized intervention strategies for fall prevention.

Gait speed decline is a hallmark of physiological aging (Schrack, Zipunnikov, Simonsick, Studenski, & Ferrucci, 2016). Slower gait speed was reported strongly associated with falls in older adults (Bauermeister et al., 2017; Verghese et al., 2009). This finding has been shown in other samples (Bauermeister et al., 2017; Ko et al., 2007; Mortaza, Abu Osman, & Mehdikhani, 2014; Verghese et al., 2009). How gait speed is further diminished and fall-related gait patterns altered with the addition of knee pain is unknown. Different mechanisms of slowing gait speed in older adults may differentiate fallers from nonfallers. The aim of this study was identifying fall-related gait patterns of older adults with the consideration of knee pain. Different gait speed associations with fall-related gait parameters were also examined in older adults with and without knee pain to specify different gait speed decline mechanisms based on experienced falls and knee pain. We hypothesized that history of falls-related gait patterns would differ depending on the presence or absence of knee pain. First, we examined gait parameters at usual gait speed between fallers and nonfallers and tested for interactions with knee pain. Then, we examined gait parameters in four different groups based on knee pain and fall status.

Methods

Participants

Data were available for 439 participants (211 women) aged 60–92 years in the Baltimore Longitudinal Study of Aging (BLSA). The BLSA is conducted by the Intramural Research Program of the National Institute on Aging; examinations performed include gait assessment at the Clinical Research Unit located in Baltimore, MD. Participants who did not have a hip or knee joint replacement, who self-reported severe knee osteoarthritis or history of stroke or Parkinson's disease, and who were able to follow instructions and safely complete the walking task unaided at their self-selected usual pace were included in the study. Within 3 days of evaluations, history of falls and knee pain were self-reported using standardized questionnaires administered by highly trained registered nurses or nurse practitioners.

History of falls was identified by a positive response to the question, “In the past 12 months, have you fallen and landed on the ground or floor?” Knee pain was identified by a positive response to the question, “In the past 12 months, have you had knee pain lasting at least 1 month?” This knee pain question is derived from the WOMAC, a standardized assessment of joint pain that has been used in multiple studies (Javaid et al., 2012). The BLSA protocol was approved by the National Institute of Environmental Health Sciences Institutional Review Board. Participants were given a detailed description of the study and consented to participate.

Gait Measurements

Procedures for gait analysis performed in the BLSA gait laboratory have been described previously (Ko, Hausdorff, & Ferrucci, 2010). In brief, participants were instrumented with 20 reflective markers at anatomical landmarks: anterior and posterior superior iliac spines, medial and lateral knees, medial and lateral ankles, toes (second metatarsal head), heels, and lateral wands over the midfemur and mid-tibia. A Vicon 3D motion capture system with 10 digital cameras (Vicon 612 system; Oxford Metrics Ltd., Oxford, UK) measured the 3D locations of all markers on the landmarks of lower extremity segments (60-Hz sampling frequency). After all markers were positioned, participants were asked to walk along a 10-m long walkway at their self-selected usual walking pace until they had completed at least three gait cycles from the left and right sides, with the full foot landing on the force platform (Ko, Ling, Schreiber, Nesbitt, & Ferrucci, 2011). The raw coordinate data of marker positions were digitally filtered with a fourth-order zero-lag Butterworth filter with a cutoff at 6 Hz. For this study, fundamental gait parameters included gait speed, stride length, stride width, double support time, and ROM during walking for lower extremity joints (hip, knee, and ankle) in the sagittal plane (kinematics).

Statistical Analysis

The characteristics and gait parameters of the study population were compared using generalized linear model (Tukey–Kramer) for persons with and without history of falls (Table 1). The presence of an interaction between history of falls and knee pain was checked to assess the need for analyses within knee pain strata. Each gait parameter was compared across four groups defined by history of falls and knee pain (G1: nonfallers without knee pain; G2: fallers without knee pain; G3: nonfallers with knee pain; and G4: fallers with knee pain) using multivariate generalized linear models and reported as mean values and standard errors (Table 2). Regression models for gait speed with other gait parameters were then developed individually for each of the knee pain/fall status groups (Table 3). All models were adjusted for age, sex, height, weight, and gait speed (except speed itself). Statistical significance was defined using a p value less than .05. We checked for collinearity by identifying variance inflation factors above four (Pan & Jackson, 2008). Statistical analyses were performed with SAS 9.2 statistical package (SAS Institute Inc., Cary, NC).

Results

Participant characteristics including age did not differ by history of falls as summarized in Table 1. Gait speed was similar by history of falls, but fallers had a wider stride width and

longer double support time than nonfallers ($p < .050$ for all). The interaction between history of falls and knee pain was significant in double support time ($p = .014$). Gait parameters were compared across the four groups in Table 2. In persons without knee pain, fallers (G2) had a longer double support time than nonfallers (G1; $p = .012$); in persons with knee pain, double support time did not differ by fall status (G4 vs. G3). Both fallers and nonfallers with knee pain had smaller knee ROM than nonfallers without knee pain (G3 vs. G1; $p = .036$, and G4 vs. G1; $p = .005$, respectively). The largest variance inflation factor was 2.5, suggesting collinearity was not an issue for the model (Pan & Jackson, 2008).

Gait speed was positively associated with stride length ($p < .001$; adjusted for sex, age, height, and weight) for all participants (see Table 3). Double support time was negatively associated with gait speed ($p < .050$) for all except fallers with knee pain (G4). In fallers with knee pain (G4), slower gait speed was associated with narrower stride width ($p = .027$) and larger hip ROM ($p = .001$). Among nonfallers without knee pain (G1), smaller hip ROM was associated with slower gait speed ($p = .003$). Larger ankle ROM was associated with slower gait speed in all participants without knee pain ($p < .001$, for G1 and G2).

Discussion

Identifying specific gait patterns of persons who have a history of falling in consideration of knee pain, a common ailment that also modifies gait characteristics, is potentially informative for interventions designed to reduce falls and maintain functioning in older adults. Without considering knee pain status, previous studies have found fallers to have prolonged double support duration, shorter stride length, increased variability, and lower strength than nonfallers (Espy, Yang, Bhatt, & Pai, 2010; Lord et al., 1996; Moreland et al., 2004; Verghese et al., 2009). Older adults with knee pain share spatiotemporal gait adaptations with older adult fallers (Barton, Levinger, Webster, & Menz, 2011; Kitayuguchi et al., 2015; Ko et al., 2015). We found an interaction between history of falls and knee pain in double support time, which may suggest that knee pain can modify compensatory strategies in recent fallers. In participants without knee pain, fallers showed elongated time in double support, which may be a compensatory strategy to improve stability only in participants who are free from knee pain. Previously reported gait patterns of fallers were confirmed in this study for longer double support time (Lord et al., 1996; Verghese et al., 2009), though the wider stride width typically observed for fallers (Mortaza et al., 2014; Taylor, Delbaere, Mikolaizak, Lord, & Close, 2013) was not evident in this study when considered with knee pain. Gait speed association with stride width in fallers with knee pain (G4) may explain existing contravention in fall-related gait patterns in stride width (Espy et al., 2010; Swanenburg, de Bruin, Uebelhart, & Mulder, 2010).

Participants with knee pain (G3 and G4; Table 3) walked with smaller knee ROM than nonfallers without knee pain (G1). This result suggests that limitation of knee rotation during one gait cycle in older adults can be a barometer for knee pain and related conditions rather than a fall-related gait pattern. Gait speed was negatively associated with ankle ROM only in participants without knee pain (G1 and G2). This can be a compensational role of the ankle in slower speed gait that is evident only in participants without knee pain (Ko et al., 2015).

Regardless of history of falls and knee pain status, gait speed was positively associated with stride length and negatively associated with double support time except for fallers with knee pain (G4). These findings confirm the widely observed relationship that gait speed is a function of spatial (stride length) and temporal (double support time) factors, which may be disrupted in the presence of multiple pathologies such as history of falls and knee pain. Although compensation strategies are likely driven by a person's perceptions that change the result in a safer, more stable gait, it is not clear that this is the case. For example, with slower speed, fallers with knee pain (G4) walked with narrower stride width and with bigger hip ROM, but not with the expected longer double support time. This gait pattern is atypical and may increase medial-lateral instability (Swanenburg et al., 2010). Limitation of pelvic adaptation for the different gait speed was reported in older adults (Gimmon et al., 2015). Persons with a history of falls and knee pain seem to exhibit gait patterns that indicate a proneness for further falls; that is, in attempting to avoid knee pain, such persons alter their gait mechanics in such a way as to create instability. Further longitudinal studies are needed in this area.

Interestingly, no fall-related differences were found in gait speed and stride length, which contrasts with previous reports of fall-related gait characteristics that did not account for knee pain (Mortaza et al., 2014; Thaler-Kall et al., 2015). In the current sample, fallers and nonfallers were similar in age and knee pain prevalence. In fact, all groups had an average gait speed of at least 1.1 m/s, which is considered a high level of physical functioning (Studenski et al., 2011). The BLSA includes high-functioning older adults, which limits the generalizability of these findings. It may also explain why all of the groups had similar gait speeds despite differences in knee pain and history of falls, as this high-functioning sample had adequate capacity to compensate for impairments. History of falls and knee pain may create larger disparities when examined in a group of older adults with greater heterogeneity in functioning. In addition, future studies should consider the severity of knee pain to allow for more detailed comparisons. A strength of the study is that the nonfallers without knee pain represent a comparison group with an average gait under ideal situations.

Interventions aiming to reduce falls or to increase/maintain walking activity levels could tailor designs including the aberrant gait characteristics identified here. For example, individuals with knee pain with a small hip ROM in relatively fast gait speed may benefit from exercises targeting strength maintenance through the full hip ROM. Among those with knee pain, relationship between stride width and gait speed should be carefully monitored and regulated to avoid possible falls.

In conclusion, the findings of this study suggest that gait characteristics of fallers and nonfallers may differ depending on the presence of other comorbidities that may impact gait, such as knee pain. For instance, fallers appear to spend more time in double stance when experiencing knee pain. Although the interaction of knee pain and history of falls was not significant with respect to hip ROM, there were distinct differences with greater hip ROM associated with faster gait speed in nonfallers without pain, whereas greater hip ROM was associated with slower gait speed in fallers with knee pain. Different associations between hip kinematics and gait speed is an important finding for better understanding how gait mechanisms in general related with falls during aging. As suggested previously, knee pain

itself can be a meaningful factor and should be a consideration in evaluating fall-related gait patterns of older adults. Interventions targeting reduction of falls or promoting regular physical activity among older adults should consider tailored approaches based on history of falls, comorbidities, and specific gait characteristics. Developing a clearer understanding of how to tailor approaches for those using various compensatory strategies could provide important insights into maintaining mobility and independence among older adults.

Acknowledgments

This research was supported entirely by the Intramural Research Program of the National Institutes of Health, National Institute on Aging, and Chonnam National University. Data for these analyses were obtained from the Baltimore Longitudinal Study of Aging, a study performed by the National Institute on Aging. All the authors declare that they have no financial or personal relationships with people or organizations that could inappropriately influence or bias this work.

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Table 1

Participant Characteristics and Gait Parameters by History of Falls

Characteristics and gait parameters	Nonfallers (N = 328)	Fallers (N =111)	Group difference	Interaction of fall × knee pain
	Mean (SE)	Mean (SE)		p value
Characteristics				
age, year	71.74 (0.44)	72.26 (0.76)	.556	.369
sex, % men	52.69 (2.77)	49.64 (4.77)	.580	.860
weight, kg	76.99 (0.84)	77.64 (1.45)	.696	.442
height, cm	168.40 (0.50)	169.07 (0.86)	.495	.684
knee pain, %	30.49 (2.57)	34.23 (4.41)	.464	NA
Gait parameters ^a				
gait speed, m/s	1.13 (0.09)	1.10 (0.02)	.088	.576
stride length, m	1.21 (0.01)	1.20 (0.01)	.067	.169
stride width, cm	10.47 (0.15)	11.09 (0.25)	.036	.243
double support time, ms	212.13 (1.71)	219.44 (2.97)	.034	.014
hip ROM, degree	38.69 (0.22)	38.83 (0.38)	.756	.799
knee ROM, degree	54.52 (0.24)	53.69 (0.41)	.081	.698
ankle ROM, degree	24.34 (0.20)	24.28 (0.34)	.888	.388

Note. All comparisons are based on Tukey's GLM. GLM = general linear model; ROM = range of motion; NA = not applicable. Significant *p* values are in bold.

^aComparisons of gait parameters controlled for age, sex, weight, height, and gait speed (except gait speed itself).

Table 2

Comparisons of Gait Parameters Between Nonfallers and Fallers Within Knee-Pain Strata

Gait parameters	Comparisons between nonfallers and fallers					
	Without knee pain			With knee pain		
	Nonfallers G1 (N = 228)	Fallers G2 (N = 73)		Nonfallers G3 (N = 100)	Fallers G4 (N = 38)	Significant difference between groups
Gait speed, m/s	Mean (SE) p value	1.14 (0.01) .326	1.10 (0.02)	1.11 (0.02) .954	1.10 (0.03)	NS
Stride length, m	Mean (SE) p value	1.21 (0.01) .113	1.19 (0.01)	1.22 (0.01) .999	1.22 (0.01)	NS
Stride width, cm	Mean (SE) p value	10.40 (0.18) .090	11.25 (0.31)	10.64 (0.27) .995	10.76 (0.43)	NS
Double support time, ms	Mean (SE) p value	209.93 (2.08) .012	222.87 (3.65)	216.92 (3.13) .834	211.93 (5.05)	NS
Hip ROM, degree	Mean (SE) p value	38.71 (0.27) .999	38.77 (0.47)	38.65 (0.40) .979	38.95 (0.65)	NS
Knee ROM, degree	Mean (SE) p value	54.97 (0.29) .615	54.26 (0.50)	53.56 (0.43) .535	52.46 (0.69)	G1 vs. G3 (<i>p</i> = .036) G1 vs. G4 (<i>p</i> = .005)
Ankle ROM, degree	Mean (SE) p value	24.23 (0.24) .937	23.95 (0.42)	24.57 (0.36) .917	25.01 (0.59)	NS

Note. All comparisons are based on Tukey's GLM. All parameters were adjusted for age, sex, weight, height, and gait speed (except gait speed itself). Significant p values are in bold. G1: nonfallers without knee pain; G2: fallers without knee pain; G3: nonfallers with knee pain; and G4: fallers with knee pain. GLM = general linear model; ROM = range of motion; NS = not significant.

Association Between Other Gait Parameters and Gait Speed Within Four Groups Based on History of Falls and Knee Pain

Table 3

Gait speed association with other gait parameters		Pain Fall Index ^a			
		Without knee pain		With knee pain	
		Nonfallers G1 (N = 228)	Fallers G2 (N = 73)	Nonfallers G3 (N = 100)	Fallers G4 (N = 38)
Stride length, m	Coefficient, $\beta 1$	0.751	1.036	1.013	1.321
	<i>p</i> value	<.001	<.001	<.001	<.001
Stride width, cm	Coefficient, $\beta 2$	0.585	0.048	0.321	0.922
	<i>p</i> value	.076	.898	.382	.027
Double support, s	Coefficient, $\beta 3$	-1.210	-0.983	-0.811	-0.531
	<i>p</i> value	<.001	.012	.005	.308
Hip ROM, degree	Coefficient, $\beta 4$	0.007	-0.003	0.001	-0.017
	<i>p</i> value	.003	.361	.771	.001
Knee ROM, degree	Coefficient, $\beta 5$	.001	-.001	.001	-.001
	<i>p</i> value	.690	.826	.749	.865
Ankle ROM, degree	Coefficient, $\beta 6$	-0.006	-0.013	-0.003	-0.005
	<i>p</i> value	.007	.003	.402	.096

Note. All parameters were adjusted for age, sex, weight, and height in GLM. GLM = general linear model; ROM = range of motion. Significant *p* values are in bold.

^aKnee Pain Fall Index: 1, nonfallers without knee pain; 2, fallers without knee pain; 3, nonfallers with knee pain; 4, fallers with knee pain.