Lateral Rhythmic Unipedal Stepping in Younger, Middle-aged and Older Adults

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ABSTRACT

Purpose: Voluntary and protective stepping performance changes with age. This has implications for the problem of falls in older adults. The purpose of this study was to examine the influence of metronome paced stepping practice on self-selected preferred rhythmic unipedal stepping performance in the medial-lateral direction among younger, middle-aged and older adults. **Methods:** Thirty-two healthy adult subjects (10 younger, 10 middle-aged, 12 older) participated. They performed rhythmic lateral stepping with their dominant limb at their preferred pace before and after 6 trials of metronome-paced stepping. **Results:** Older subjects had longer stride periods than young and middle-aged subjects prior to metronome pacing. Older subjects exhibited a 25% decrease in preferred stride period between pre- and postpacing trials. This is compared to a 15% and 11% decrease exhibited by middle-aged and younger subjects respectively. Preferred stride period was similar for older subjects as compared to younger and middle-aged subjects after paced practice. Modification of the stride period occurred mainly during the stance phase of rhythmic stepping. **Conclusions:** Comparable stride periods across groups after pacing suggest stepping performance is modifiable. Brief intervals of paced stepping may offer older adults a short-term benefit to stepping performance.

Key Words: stepping, rhythm, balance, aging

INTRODUCTION

Stepping is ubiquitous in functional activity. A step is integral for intentional actions such as the initiation and ongoing execution of walking, turning, and transferring to different surfaces, as well as a commonly employed tactic for bodily protection when faced with real or perceived threats to balance.

Understanding how aging affects stepping is important for several reasons. First, human aging is associated with changes across a variety of physiological systems and changes in functionally important anatomic structures related to balance control.[1,2] Second, falls are a major cause of morbidity and mortality for community-dwelling people over the age of 65.[3] Of all hip fractures occurring in adults over the age of 60, approximately 90% are the result of a fall.[4] Lateral body motion and hip fractures are related and falls frequently occur during transfers, turning, and stepping.[5] Therefore, falling may be related to changes in stepping performance and altered stepping may be viewed as an emergent feature of multiple impairments associated with falls.[6,7]

Differences in stepping behavior in older adults (OA) versus younger adults (YA) exist. For example, temporal gait characteristics defining stepping performance are altered among OA. Comfortable gait speed declines with age.[8-10] While step length and width tend not to be different purely as a function of age, step width variability has recently been shown to be greater in OA[11] and is a predictor of falls.[12]

Under reaction time conditions, OA's voluntarily generated step initiation is prolonged due to longer reaction and weight transfer times prior to limb removal.[13-16] In contrast, studies of externally induced protective stepping have identified that steps in OA can occur as rapidly as those seen in YA.[17-19] However, induced steps have been shown to occur more frequently, are initiated for smaller perturbations, and can be more laterally directed.[19-21] The occurrence of multiple and lateral steps in response to forward perturbation suggests lateral instability may be a particularly important problem for OA.[22] Finally, it has been shown that several weeks of voluntary or protective step training can decrease voluntary step initiation time in both OA and YA.[23] Therefore, step performance may be modifiable with practice.

In summary, OA perform voluntary stepping more slowly than YA. Yet step timing appears to be modifiable under mechanical perturbation and/or training conditions. However, many studies examine stepping as a discrete event: initiate 1 step to a cue; respond to the perturbation with 1 protective step. Stepping, through foot placement and limb loading/unloading, is functionally relevant for balance during walking.[24] Walking is a continuous task. The question was posed whether OA performed rhythmic, continuous stepping under a self-selected (preferred speed) condition more slowly than YA and middle-aged adults (MA). Additionally, if preferred stepping were to be followed by a brief bout of external, sensory (nonmechanical) pacing, what effect might this have on preferred step timing performance? Therefore, the purpose of

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this study was to examine the influence of metronome paced stepping practice on self-selected preferred rhythmic stepping performance in the medial-lateral (ML) direction among YA, MA, and OA.

METHODS

Subjects

Thirty-two adult subjects (23 female, 9 male) were recruited through the University of Connecticut and surrounding community. Subjects had to be healthy, community-dwelling adults without a history of falling or major neurological or musculoskeletal medical condition. Older adult participants were screened for fall risk including a history, general mobility test (Timed Up & Go), cognitive screening (Mini Mental State Examination), lower extremity sensation (proprioception, monofilament), and medication use. No subject was taking a sedative or antidepressant known to affect balance and no OA participating in this study was considered to be at risk for falling. This study was reviewed and approved by the University and all subjects provided written informed consent.

Subjects were grouped according to age. Of the 32 subjects, 10 were YA (21-29 years, $\bar{x}$ = 23.2, SD= 2.65, 8 female, 2 male), 10 were MA (40-54 years, $\bar{x}$ = 47.2, SD= 4.73, 7 female, 3 male), and 12 were OA (66-78, $\bar{x}$ = 71.75, SD= 3.38, 8 female, 4 male). The mean height of the subjects was 1.69 m (SD= 0.05) for the YA, 1.71 m (SD= 0.09) for the MA, and 1.7 m (SD= 0.13) for the OA. The mean mass was 61.83 kg (SD= 8.07) for the YA, 72.98 kg (SD= 11.84) for the MA, and 75.77 kg (SD= 16.23) for the OA.

Definition of the Stepping Task

We examined rhythmic unipedal stepping in the ML direction. This is defined as a series of repeated step-out (laterally) and step-in movements using 1 lower limb. Thus there is only 1 stepping limb and always one support limb. One reason for choosing this stepping task is that it is useful for evaluating how weight is transferred and how lower limbs are loaded and unloaded during stepping. Compared to YA, OA have prolonged weight transfer times[13] and more limb load asymmetry in preparation to make a step.[25] Figure 1 shows one stride of rhythmic, unipedal stepping in the ML direction.

Preferred stepping performance

Subjects stood comfortably on 2 adjacent force platforms (AMTI, Watertown, Mass) with arms folded and the heels initially set a distance from each other representing approximately 12% of their body height.[26] Subjects were instructed to rhythmically step out to the side a comfortable distance with their right lower limb and return it to the initial position at their preferred stepping pace. All subjects were right leg dominant as determined by self-reported kicking preference. Subjects were given practice to become familiar with the instruction and to set their preferred unipedal stepping rhythm. Subjects were explicitly told that their preferred stepping pace should be 'a natural, comfortable pace.' No attempt was made by the experimenter to define 'comfortable distance' so that the step length was not formally constrained. After practice, subjects were allowed as much time as necessary to get into their preferred stepping rhythm. Twenty seconds of data collection was initiated approximately 5 seconds after the subject stated that he or she was in this preferred stepping rhythm. One, 20 s trial of preferred stepping was performed at the beginning of the experimental session. A second trial of preferred stepping was performed at the end of the experimental session, after a series of metronome-paced stepping trials.

Paced stepping practice

After the first preferred stepping trial, subjects performed six, '70 s trials of rhythmic unipedal stepping to the pace of a metronome. Subjects were instructed 'to step to the beats of the metronome so that their stepping foot was on the ground at each beat. The metronome pacing consisted of frequency plateaus increasing from 1.0 to 2.8 Hz then decreasing to 1.0 Hz in 0.6 Hz steps. A minimum of 5 minutes of seated rest occurred between each of the 6 pacing trials. These 6 trials included 3 forward-directed stepping trials and 3 ML stepping trials.

Data Collection and Processing

Step limb motion was recorded using a Qualisys (Gothenburg, Sweden) motion capture system (6 cameras, sampling rate 100 Hz). For the purposes of this report, only the surface reflective marker over the second metatarsal head of the right stepping

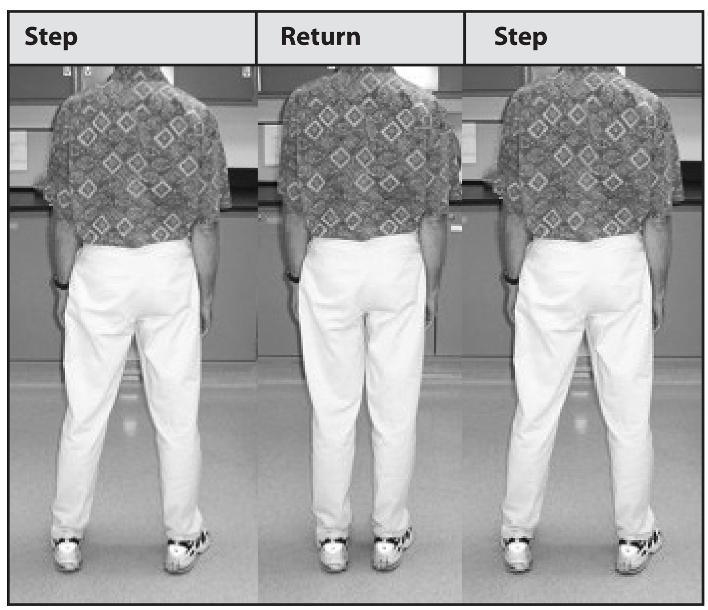

Figure 1. Lateral rhythmic unipedal stepping consists of a series of repeated stepping movements with one lower limb. A step-out to the side, a return towards midline, and subsequent step-out denotes a stride.

foot is reported as a representation of the step kinematics.

A 3D motion analysis software package (Visual3D™, version 3.13, C-Motion, Inc., Rockville, Md) was used to smooth the motion data using a low-pass second order Butterworth filter with a cutoff frequency of 6 Hz. Visual3DTM software was used to identify peak position values from the foot marker time series (Figure 2). These peak values represent the position of the foot marker at the landing phases of step-out and step-in.

Dependent Measures and Data Analysis

Dependent variables included stride period, stance and swing times, and step length. Stride period, the time from one step-out movement to the next, was calculated based on lift-off times (denoted by the arrows in Figure 2) using the foot marker data. Landing times were also identified so that the stride could be evaluated with respect to stance and swing phases. Step length was calculated by comparing peak position values for the step-out and its step-in return position. This value was normalized by dividing by body height for each subject.

SPSS (v12.0, Chicago, Ill) was used for all data analysis. Means and standard deviations (SDs) were calculated for the dependent variables. A 3 (group) x 2 (time) repeated measures analysis of variance (ANOVA) was performed on the stride period dependent variable. A repeated measures ANOVA was subsequently performed to elaborate on where within the stride any changes occurred via a 3 (group between-subject factor) x 2 (time) x 2 (phase: stance, swing) mixed model. A repeated measures ANOVA was performed on step length. Significance was set at the $P = .05$ level.

RESULTS

The means and SDs for the ML stepping stride period, stance and swing times, and step length are listed in the Table. Repeated measures ANOVA did not reveal a significant main effect for group on the stride period but did demonstrate a significant effect of time, $F(1,29) = 52.45$, $P < .001$, and a time x group interaction, $F(2,29) = 4.5$, $P = .02$. Older adults exhibited a 25% decrease in stride period from the initial pre- to post-pacing preferred stepping trial. Middle-aged adults decreased stride period 15% and YA decreased stride period 11%. The lack of a main effect of group is attributable to this larger reduction in preferred stride period for the OA after metronome pacing and this is borne out by the time x group interaction. In this connection, separate univariate analyses on group revealed that OA were slower than YA during the prepacing trial ($F(1,20) = 10.50$, $P = .004$) but not during the postpacing trial.

A 3 x 2 x 2 (group x time x stepping phase) repeated measures ANOVA revealed, in addition to the main effect of time and time x group interaction (see above), a significant effect of stepping phase, $F(1, 29) = 70.01$, $P < .001$. There was also a time x stepping phase interaction, $F(1, 29) = 34.94$, $P < .001$. In summary, stance times were larger than swing times and stance times decreased between pre- and postpacing trials while swing times remained relatively unchanged. Therefore, decreases in stride period from pre- to postpacing trials were largely attributable to adjustments in stance time. Older adults, having longer stance times, decreased their stance time by 36% as compared to MA (23%) and YA (16%) from the pre- to postpacing condition. This is borne out by the time x group interaction, $F(2, 29) = 4.59$, $P = .019$, and time x phase x group interaction, $F(2, 29) = 3.41$, $P = .047$. These temporal adjustments had no effect on step length as the analysis revealed no significant differences between groups or across time.

DISCUSSION

There are several noteworthy results. First, the OA tended to initially select a slower unipedal stepping rhythm, as defined by stride period, than YA and MA. Second, preferred stride period was comparable across groups following metronome-paced stepping. Third, stance times were always longer than swing times and stance duration decreased while swing duration

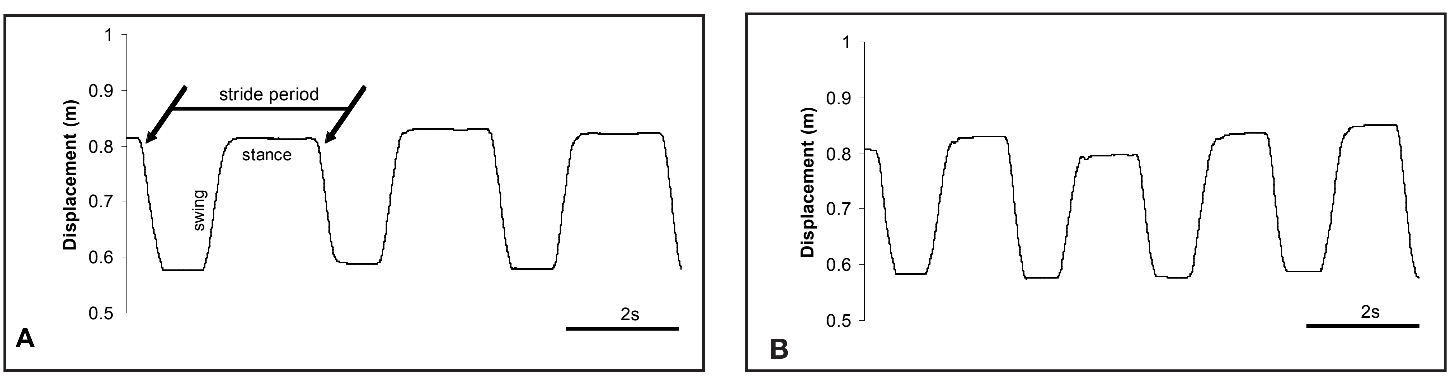

Figure 2. Truncated (10s) time series of the right foot marker for an older adult subject during preferred rhythmic stepping before (A) and after (B) metronome pacing. Ordinate represents absolute displacement values with increasing values representing step out laterally. Stride period is identified (see also Figure 1) from the lift-off of the foot marker from the step-out positions.

Table. Means (and SD) for Step Characteristics During Preferred Rhythmic Stepping Measured Pre- and Postmetronome Pacing

Characteristic	Time	Younger Adults	Middle-aged Adults	Older Adults
Stride Period (s)	Prepacing	2.12 (0.26)	2.40 (0.60)	2.56 (0.36)
	Postpacing	1.88 (0.23)	2.02 (0.47)	1.92 (0.32)
Stance Time (s)	Prepacing	1.20 (0.21)	1.48 (0.45)	1.61 (0.23)
	Postpacing	1.00 (0.21)	1.13 (0.40)	1.03 (0.26)
Swing Time (s)	Prepacing	0.91 (0.09)	0.92 (0.18)	0.96 (0.13)
	Postpacing	0.87 (0.11)	0.89 (0.14)	0.89 (0.15)
Normalized Step Length	Prepacing	0.12 (0.02)	0.11 (0.02)	0.11 (0.02)
	Postpacing	0.12 (0.02)	0.13 (0.02)	0.11 (0.02)

remained relatively unchanged from the pre- to postpacing trial. Therefore the reduction in preferred stride period after pacing is largely attributable to the modulation of stance duration. Lastly, lateral step length was not significantly different across groups nor was it affected by the metronome-pacing condition.

Older adults in this study had the longest preferred stride periods during the prepacing trial. Many studies have identified age-related changes in movement speed.[8-10,13-16,27] The specific nature of voluntary stepping, be it a single, discrete event as examined under reaction time conditions, or a rhythmical, ongoing activity as seen here and with gait, does not change the outcome that OA perform stepping more slowly than YA. It also appears that OA are slower to step regardless of instructions related to speed of performance: they step in place and walk slower than YA whether they are moving at their preferred rhythm or when instructed to walk as fast as possible.[28]

Stance duration was disproportionately longer in OA in this study. This parallels reports that weight transfer time during reaction time stepping is disproportionately prolonged in OA compared to YA.[13] Weight transfer time is the time when body weight is transferred to a support limb prior to stepping limb withdrawal. The greatest requirement for body weight transfer during rhythmic unipedal stepping in the ML direction is when the limb has stepped out and then must return medially. From these 'stance-out' to 'stance-in' postures the body has traveled laterally (thus loading the limb) and then must return medially before limb liftoff can occur. Prolonged stance duration in OA may reflect a prolonged postural function; the loading and unloading necessary for first corralling and then propelling the body back towards the support limb. Therefore, the age-related differences in stance duration seen here may reflect unique challenges facing OA when dealing with body weight transfer.

It has recently been demonstrated that healthy OA women without a history of falling have altered peak torque and rate of torque development capability, in hip abductor and adductor musculature.[29] These muscles and their torque-generating capability when the foot is in contact with the ground, are important for lateral stability in standing,[30] body weight transfer during step initiation,[31] as a line of defense for balance recovery to ML perturbations,[32] and ML balance control during walking.[33] It is conceivable then that age-related changes in the torque generating capacity of key postural muscles for stepping may modify preferred stepping rhythms in OA. On the other hand, prolonged stance duration may reflect a strategic adaptation by OA to minimize perturbations induced by lateral body motion.[34]

Comparable preferred stepping rhythms, as defined by stride period, between YA, MA, and OA were observed after metronome pacing. Stride periods were always smaller in the postpacing trial but OA reduced their stride period disproportionately more than MA and YA. The modulation of preferred unipedal stepping under the present conditions typically occurred when the stepping foot was in contact with the support surface as evidenced by the reduction in stance duration. In contrast, swing duration and step length were not different between groups, nor did they change significantly as a function of time. This is consistent with the general rule that increases in stepping frequency (shorter stride periods) during locomotion are due to modulation of stance duration.[35-37]

Modification of postpacing voluntary, self-selected stepping execution times in this study parallels some results in the literature. First, the initiation of a protective step by OA has been shown to be as fast as YA even though voluntary steps tend to be slower.[17,18,38] Second, reductions in voluntary step initiation timing have been shown to occur with step training[23] apparently independent of the nature of the training (ie, voluntary or mechanically-induced).

The modulation of stance duration in this study was not due to an intentional production of faster or more forceful steps because the instruction was to step at a preferred rhythm (not as fast as possible). This instruction did not change from beginning to end. Rather, it is possible that the reduction in stance duration is the result of practice and its effect on the management of the postural demands of the task. A short-term performance effect could have resulted from having to step at a range of pacing frequencies within the pacing condition. These frequencies may be a challenge to balance, specifically body weight transfer. Older adults' stance duration may have decreased disproportionately because they received a form of stepping practice that modified the particular dynamics of limb loading and unloading necessary for postural and balance maintenance during stepping. For example, paced stepping may have influenced neural (internal oscillatory processes, sensory feedback), biomechanical (rate of force development, global stiffness), and behavioral (attention, confidence) factors that subsequently influenced preferred stepping rhythms.

There are several limitations to this study. First, the preferred stepping scenario tested here does not definitively address these issues. Preferred stepping does not put limits on movement duration like stepping under the instruction 'move as fast as possible.' Moreover, real world protective stepping is often performed under time-critical situations. Second, the extent to which reductions in preferred stride period is uniquely a function of pacing and would be maintained over time remains unclear. We do not know whether subjects would have modified their preferred stepping rhythm without metronome pacing from one trial to the next. It was not the intent of the present study to evaluate a control group that would not have experienced a pacing condition. Third, all OA participants were independent, community-dwelling, and considered themselves healthy. Whether similar results would be observed in OA with a history of falling or with known balance deficits is not known.

The results of this study may, however, offer suggestions for further work and for the development of clinical interventions to improve stepping performance in OA. For example, if differences in preferred voluntary stepping between groups can be minimized by a bout of metronome pacing, then the impact of paced stepping on rapid voluntary and protective step initiation should be examined. Common neuromuscular mechanisms subserve stepping, whether rhythmic and voluntary or protective and reflexive in nature.[39] These mechanisms are sensitive to experience, practice, and/or recent performance.[40] Therefore, it is conceivable that paced rhythmic stepping practice may improve, at least temporarily, voluntary and protective stepping function in OA. On the other hand, an OA's natural gait speed could be temporarily increased or at least the relationship between stance and swing times influenced with a few trials of rapid, paced stepping. Whether or not this would improve response time to perturbations in real world environments remains to be determined. Lastly, hip abductor muscles play a role in limb loading/unloading, weight shifting, and lateral stepping. Adults exhibit declines in muscle performance as they age and decreased muscle strength is a risk factor for falling.[41,42] We are presently examining the use of resistance during paced stepping as a form of strengthening and as a graded challenge to balance.

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REFERENCES

1. Lord SR, Clark RD. Simple physiological and clinical tests for the accurate prediction of falling in older people. *Gerontology.* 1996;42:99-203.
2. Lord SR, Lloyd DG, Li SK. Sensori-motor function, gait patterns and falls in community-dwelling women. *Age Ageing.* 1996;25:292-299.
3. Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. *N Engl J Med.* 1988;319:1701-1707.
4. Melton LJI, Chao EYS, Lane J. Biomechanical aspects of fractures. In: Riggs BL, Melton LJ, eds. *Osteoporosis: Etiology, Diagnosis, and Management.* New York, NY: Raven Press; 1988:111-131.
5. Cumming RG, Klineberg RJ. Fall frequency and characteristics and the risk of hip fracture. *J Am Geriatr Soc.* 1994;42:774-778.
6. Rogers MW. Disorders of posture, balance, and gait in Parkinson's disease. *Clin Geriatr Med.* 1996:825-845.
7. Lord SR, Fitzpatrick, RC. Choice stepping reaction time: a composite measure of falls risk in older people. *J Gerontol A Biol Sci Med Sci.* 2001;56A:M627-M632.
8. Himann JE, Cunningham DA, Rechnitzer PA, Paterson DH. Age-related changes in speed of walking. *Med Sci Sports Exerc.* 1988;20:161-166.
9. Oberg T, Karsznia A, Oberg K. Basic gait parameters: Reference data for normal subjects, 10-79 years of age. *J*

Rehabil Res Dev. 1993;30:210-223.

10. Lusardi MM, Pellechia GL, Schulman M. Functional performance in community living older adults. *J Geriatr Phys Ther*. 2003;26:14-22.
11. Owings TM, Grabiner MD. Variability of step kinematics in young and older adults. *Gait Posture.* 2004;20:26-29.
12. Maki BE. Gait changes in older adults: Predictors of falls or indicators of fear? *J Am Geriatr Soc.* 1997;45:313-320.
13. Patla AE, Frank JS, Winter DA, Rietdyk S, Prentice S, Prasad S. Age-related changes in balance control system: initiation of stepping. *Clin Biomech*. 1993;8:179-184.
14. Stemmons Mercer V, Sahrmann SA, Diggles-Buckles V, Abrams RA, Norton BJ. Age group differences in postural adjustments associated with a stepping task. *J Mot Behav*. 1997;29:243-253.
15. Rogers MW, Kukulka CG, Brunt D, Cain TD, Hanke TA. The influence of stimulus cue on the initiation of stepping in young and older adults. *Arch Phys Med Rehabil*. 2001;82:619-624.
16. Luchies CW, Schiffman J, Richards LG, Thompson MR, Bazuin D, DeYoung AJ. Effects of age, step direction, and reaction condition on the ability to step quickly. *J Gerontol A Biol Sci Med Sci*. 2002;57A:M246-M249.
17. Luchies CW, Alexander NB, Schultz AB, Ashton-Miller, J. Stepping responses of young and old adults to postural disturbances: kinematics. *J Am Geriatr Soc*. 1994;42:506-512.
18. Luchies CW, Wallace D, Pazdur R, Young S, DeYoung AJ. Effects of age on balance assessment using voluntary and involuntary step tasks. *J Gerontol A Biol Sci Med Sci*. 1999;54A:140-M144.
19. Rogers MW, Hedman LD, Johnson ME, Cain TD, Hanke TA. Lateral stability during forward-induced stepping for dynamic balance recovery in young and older adults. *J Gerontol A Biol Sci Med Sci*. 2001;56A:M589-M594.
20. Maki BE, McIlroy WE. The role of limb movements in maintaining upright stance: The "change-in-support" strategy. *Phys Ther*. 1997;77:488-507.
21. Pai Y-C, Rogers MW, Patton J, Cain TD, Hanke TA. Static versus dynamic predictions of protective stepping following waist-pull perturbations in young and older adults. *J Biomech*. 1998;31:1111-1118.
22. Rogers MW, Mille ML. Lateral stability and falls in older people. *Exerc Sport Sci Rev*. 2003;31:182-187.
23. Rogers MW, Johnson ME, Martinez KM, Mille LM, Hedman LD. Step training improves the speed of voluntary step initiation in aging. *J Gerontol A Biol Sci Med Sci*. 2003;58A:46-51.
24. Winter DA. *A. B. C. (Anatomy, Biomechanics, and Control) of Balance during Standing and Walking.* Waterloo, Ontario, Canada: Waterloo Biomechanics; 1995.
25. Henriksson M, Hirschfeld H. Physically active older adults display alterations in gait initiation. *Gait Posture.* 2005;21:289-296.
26. McIlroy WE, Maki BE. Preferred placement of the feet during quiet stance: Development of a standardized foot placement for balance testing. *Clin Biomech.* 1997;12:66-70.
27. Vanneste S, Pouthas V, Wearden JH. Temporal control of rhythmic performance: A comparison between young and old adults. *Exp Aging Res*. 2001;27:83-102.
28. Craik R. Changes in locomotion in the aging adult. In: Woollacott M, Shumway-Cook A, eds. *Development of Posture and Gait Across the Life Span.* Columbia, SC: University of South Carolina Press; 1989:176-201.
29. Johnson ME, Mille ML, Martinez KM, Crombie G, Rogers MW. Age-related changes in hip abductor and adductor joint torques. *Arch Phys Med Rehabil*. 2004;85:593-597.
30. Winter DA, Prince F, Stergiou P, Powell C. Medial-lateral and anterior-posterior motor responses associated with centre of pressure changes in quiet standing. *Neurosci Res Commun.* 1993;12:141-148.
31. Rogers MW, Pai Y-C. Patterns of muscle activation accompanying transitions in stance during rapid leg flexion. *J Electromyogr Kinesiol*. 1993;3:149-156.
32. Rietdyk S, Patla AE, Winter DA, Ishac MG, Little CE. NACOB presentation CSB New Investigator Award. Balance recovery from medio-lateral perturbations of the upper body during standing. *J Biomech.* 1999;32:1149-1158.
33. MacKinnon CD, Winter DA. Control of whole body balance in the frontal plane during human walking. *J Biomech*. 1993;26:633-644.
34. Mille ML, Johnson ME, Martinez KE, Rogers MW. Age-dependent differences in lateral balance recovery through protective stepping. *Clin Biomech.* 2005;20:607-616.
35. Wilson DM. Insect walking. *Annu Rev Entomol.* 1966;11:103-122.
36. Pearson KG, Misiaszek JE, Fouad K. Enhancement and resetting of locomotor activity by muscle afferents. *Ann N Y Acad Sci*. 1998;860:203-215.
37. Orlovsky GN, Deliagina TG, Grillner S. *Neuronal Control of Locomotion: From Mollusk to Man.* Oxford: Oxford University Press; 1999.
38. Jensen JL, Brown LA, Woollacott MH. Compensatory stepping: the biomechanics of a preferred response among older adults. *Exp Aging Res.* 2001;27:361-376.
39. Hultborn H. State-dependent modulation of sensory feedback. *J Physiol.* 2001;533:5-13.
40. Pearson KG Neural adaptation in the generation of rhythmic behavior. *Annu Rev Physiol.* 2000;62:723-753.
41. Simpson JM. Elderly people at risk of falling: The role of muscle weakness. *Physiotherapy*. 1993;79:831-835.
42. Nevitt MC, Cummings SR, Hudes ES. Risk factors for injurious falls: a prospective study. *J Gerontol A Biol Sci Med Sci*. 1991;46:M164-170.