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Review Article

Impact of cognitive fatigue on gait and sway among older adults: A literature review

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ABSTRACT

Cognitive fatigue is an alteration in central nervous system (CNS) processing due to prolonged performance of mentally demanding tasks. Decreased gait speed and increased stride length variability have been noted in cognitively fatigued older adults (≥65 years). Further, cognitive fatigue may weaken the visual, vestibular, and proprioceptive systems of the CNS, contributing to increased postural sway. Detriments in gait and sway caused by cognitive fatigue could increase fall risk. The objective of this literature review was to evaluate the impact of cognitive fatigue on changes in gait and postural sway and its role in fall risk.

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By the year 2030, over 20% of the population will be over the age of 65 (Center for Disease Control and Prevention, 2015). Older adults (i.e. individuals aged 65 years and older) are more prone to falls. In 2013, direct fall-related costs were estimated to exceed $34 billion, and falls incidence rates and associated financial costs continue to rise (Center for Disease Control and Prevention, 2015). Falls among older adults have been known to cause institutionalization, premature mortality, and increased use of healthcare services (Rubenstein, 2006). Approximately two-thirds of unintentional injury deaths within the older adult

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population are attributed to falls, and over 45% of those aged 75 years and older experience a fall each year (Cebolla et al., 2015). The prevalence of falls among the older adult population may be related to diminished neuromuscular functioning, which accompanies natural aging. Examples include reductions in balance, muscle strength, peripheral sensation, vision, and cognition, which have all been associated with increased fall risk among older adults (Martin et al., 2013).

Common cognitive disorders among the older adult population including stroke, Parkinson's disease, and dementia (including mild cognitive impairment) have been reported to increase fall risk (Fischer et al., 2014). More recently, declines in the cognitive abilities of healthy older adults have been associated with increased fall risk (Herman et al., 2010). The most common reason for mildly impaired cognitive function among older adults is cognitive fatigue, a failure to sustain attention for optimal performance (Holtzer et al., 2011). Consequently, cognitive fatigue may cause changes in gait and postural sway among older adults because both tasks require higher order neurological processes (Herman et al., 2010). To the authors knowledge there is no current literature that examines the role of cognitive fatigue in falls and fall risks. Therefore, the objective of this literature review was to examine the current literature to assess the role that cognitive fatigue may have on gait and postural sway. A better understanding of cognitive fatigue's role in gait and postural sway may raise awareness among researchers and healthcare professionals about this important risk factor and guide future efforts to integrate this knowledge into fall prevention protocols and future studies to examine the role of cognitive fatigue in fall risk factors.

1. Methodology

A literature search was conducted from July 1, 2015 to July 5, 2015 using Medline, Science Direct, Pubmed, CINAHL, and Cochrane library databases for articles published between June 2005 and June 2015. The following combination of mesh terms were used "fall risks" or "falls" and "cognitive fatigue" or "central fatigue".

We were unable to find literature that directly linked central or cognitive fatigue to falls, therefore we changed our search strategy to reflect a literature review to indirectly link central or cognitive fatigue to falls and fall risks. To conduct the literature review we used the following mesh terms "fall risk older adult" or "fall risk elderly"; "central fatigue elderly" or "mental fatigue elderly" or "cognitive fatigue elderly"; "fatigue and gait elderly" or "fatigue and gait older adults"; "fatigue and sway elderly" "fatigue and sway older adults".

2. Cognitive fatigue

Fatigue is a temporary loss of strength and energy resulting from hard physical or mental work (Gardiner et al., 2009). The word "fatigue" can refer to peripheral fatigue or central fatigue (Holtzer et al., 2011). Cognitive fatigue, a component of central fatigue (Holtzer et al., 2011), is a psychobiological state caused by prolonged periods of demanding cognitive activities (Marcora et al., 2009). It is characterized by feelings of tiredness and lack of energy (Marcora et al., 2009), and results in failure to maintain attention necessary for optimal performance (Holtzer et al., 2011; Shortz et al., 2015). Acute cognitive fatigue is a common part of everyday activities, such as driving through traffic (Marcora et al., 2009), but can also arise from sustained performance of multiple tasks requiring mental effort, such as fatigue after a work day in the office (van der Linden et al., 2003). Fatigue is usually accompanied by weariness and reduced alertness, which could contribute to decreased productivity and accidents (Liu et al., 2010).

Prolonged performance of a mentally-demanding task causes changes in the activation of the prefrontal cortex (Tanaka et al., 2014), an area of the brain involved with executive function. Tanaka et al. (2014) found that performing a mental fatigue-inducing task causes increased beta-frequency band power, which may be related to decreased brain alertness and arousal levels (Tanaka et al., 2014).

Individuals experiencing cognitive fatigue have reported difficulty when performing tasks that require attention and concentration (Boksem et al., 2006). Decreased efficiency of attentional allocation causes a decline in efficiency when performing a task during or following a mentally-fatigued state (Boksem et al., 2006). Another reason for decreased performance when cognitively fatigued may be impaired action monitoring (i.e. the ability to use environmental information to adjust ongoing behavior) (Boskem et al., 2005). Cognitive fatigue among older adults may lead to changes in gait and postural control, both of which require cognitive processes (Herman et al., 2010).

3. Gait

Normal gait requires stability to provide antigravity support of body weight, mobility to allow smooth motion, and motor control while body weight is transferred from one limb to another (Gamble and Rose, 1994). Gait has been previously used as a reliable clinical tool to predict functional mobility (Podsiadlo and Richardson, 1991) and falls (Shumway-Cook et al., 2000) among older adults. Additionally, gait tests have been commonly used as the motor task component for dual-task assessments (Montero-Odasso et al., 2012). Several versions of gait tasks are available, including 3-m walking (i.e. Time Up-and-Go), walking at a preferred or fast speed (i.e. 2-Minute Walk Test), with or without turns, and with or without obstacles, with the assumption that walking at a fast speed, with turns, and with obstacles, is more challenging (Hall et al., n.d.).

Arm swing and gait symmetry are other characteristics that are correlated with local dynamic stability (Punt et al., 2015). Increased gait variability and decreased symmetry has been consistently observed among older adults (LaRoche et al., 2014) due to the normal aging process (Barak et al., 2006). For individuals older than 70 years of age, changes in gait include average gait speed decreases 12–16% per decade; stride length decreases at a given walking speed; stride frequency increases; and double-support duration increases (Barak et al., 2006). These changes in gait may be due to reduction of energy costs, compensation for muscle weakness, balance impairments, and coping with increased walking variability (Barak et al., 2006).

Another possible explanation for gait declines among older adults may be reduced cognitive functioning (Amboni et al., 2013). Gait and cognition impairments are common among older adults, and they often coincide (van Iersal et al., 2008). Gait is considered an activity requiring attention, memory, and planning (Theill et al., 2011), as well as motivation and judgment (Amboni et al., 2013). Cognition as a contributor to gait abnormalities has been experimentally supported by the dual-task (DT) paradigm (i.e. changes in gait from a single task to a dual task condition) (Amboni et al., 2013).

4. Postural stability and sway

The ability to maintain good balance is critical for most activities of daily living (Hanson et al., 2010). Balance, or postural control, describes an ability to keep the body in an upright position, and when necessary, make adjustments to this position (Hanson et al., 2010). Visual, vestibular, and proprioceptive organs interact to maintain balance by detecting environmental cues and translating these cues to signals that are processed by the central nervous system (Hanson et al., 2010).

Sensorimotor tasks, such as postural control, were previously considered automatic (Smolders et al., 2010); however, postural stability is a complex skill, dependent on coordination of the motor and sensory systems through higher order neurological processes, particularly executive functioning (Muir-Hunter et al., 2014). Executive functioning is required for planning movements, divided attention, and responding to changes within the environment (Muir et al., 2012). Attentional demands needed to minimize sway increase with aging, pathology, and task difficulty (Bisson et al., 2011).

The normal aging process consists of neurodegenerative and neurochemical changes, resulting in less efficient visuospatial and sensorimotor processing (Bergamin et al., 2014), and therefore, decreased postural control. Age-related decrements in postural stability are observed during standing and when responding to environmental perturbations (Sturnieks et al., 2008). Numerous studies (Bergamin et al., 2014; Granacher et al., 2011) have measured balance as a function of age among healthy older adults and have found increased sway, decreased one leg standing time, and a decrease in function of the base of support (attributed to decreased toe flexor strength) (Bryant et al., 2005) to be indicative of decreased postural regulatory abilities.

5. Impact of cognitive fatigue on gait

Walking while performing a secondary task, or DT, that demands attention has been used to assess the relationship between cognition and gait. Four studies presented in Table A.1 measured gait parameters among samples of older adults walking while performing a simultaneous cognitive task (DT condition), and compared the results to the gait parameters measured while walking alone (single task condition). The findings of Hall et al. (2011) (Hall et al., n.d.) and LaRoche et al. (2014) (LaRoche et al., 2014) may suggest changes in gait parameters observed during DT walking are a consequence of reduced cognitive function associated with aging. Hall et al. (2011) (Hall et al., n.d.) found that cognitive factors contributed to participants' ability to walk and perform a complex cognitive task (Hall et al., n.d.), and participants walked slower under the DT condition than the single task condition regardless of the cognitive task being performed (Hall et al., n.d.).

LaRoche et al. (2014) found changes in gait parameters under DT conditions for participants in their 70s, but not for participants in their 50s and 60s. In general, gait variability across conditions was greatest for subjects in their 70s (LaRoche et al., 2014). These results may support the hypothesis that cognitive fatigue increases gait variability among older adults. Competition for attentional resources is observed under DT because the brain is forced to unconsciously decide which task to prioritize (Beauchet et al., 2005).

Walking while cognitively fatigued may be viewed as a DT condition because the attention required for stable gait is diminished as a result of fatigue. Cognitive fatigue may be analogous to the secondary cognitive tasks used in previous DT studies; both cognitive fatigue and the secondary cognitive task diminish the attentional resources that are needed for stable gait.

Verlindin et al. (2014) performed cognitive and gait assessments with 1232 participants from the Rotterdam Study (population based study in the Netherlands to explore causes and determinants of chronic diseases among middle-aged and older adults). Cognitive assessments consisted of tasks testing memory, information processing speed, fine motor speed, and executive function. Seven independent domains were used to assess gait, namely rhythm, variability, phases, pace, tandem, turning, and base of support. Information processing speed was associated with rhythm, which reflects temporal gait parameters including cadence, stance time, and swing time. Fine motor speed was associated with tandem, which reflects amount of errors during tandem walk including side steps and double steps. Executive function was associated with pace, which reflects distance related variables including stride length and gait velocity (Verlindin et al., 2014). These findings show that cognition and gait have a distinct pattern of association (Verlindin et al., 2014). Therefore temporary cognitive impairments due to fatigue may cause gait changes that could be detrimental to older adults.

6. Impact of cognitive fatigue on sway

Many studies (Holtzer et al., 2011; Cook et al., 2007) have concluded that cognitive fatigue decreases concentration on and attention to a given task. Although maintaining stable upright posture requires minimal attention, impaired cognitive functioning among older adults could cause balance loss. Regulation of postural sway requires the visual, vestibular, and proprioceptive systems; these sensory systems are weakened as a consequence of the normal aging process (Sullivan et al., 2009), and impaired as cognitive fatigue progresses (Van Iersel et al., 2007).

The DT paradigm has been used in previous studies to investigate cognition and gait, as well as cognition and postural sway. Van Iersel et al. (2007); Smolders et al. (2010), and Granacher et al. (2011) (Table A.2) found postural control among older adults decreased under DT conditions. Van Iersel et al. (2007) found a cognitive DT influenced balance control among physically fit older adults directly and indirectly through decreased gait velocity, which could be a strategy to maintain balance during walking in more difficult circumstances (Van Iersel et al., 2007).

Cognitive fatigue decreases the ability to maintain cognitive performance; therefore, a cognitively-fatigued older adult might have diminished balance capabilities. Studies by Smolders et al. (2010) and Granacher et al. (2011) compared the effects of a cognitive DT on postural sway between young adults and older adults. Both studies found greater sway among the older adults, irrespective of task condition (Smolders et al., 2010; Granacher et al., 2011). These results suggested that postural control becomes more cognitively-demanding with age as a consequence of sensorimotor deficits observed among older adults (Smolders et al., 2010; Granacher et al., 2011).

Sullivan et al. (2009) and Muir-Hunter et al. (2014) explored the relationship between cognition and postural sway using clinical measures of cognitive function and balance performance tests. Muir-Hunter et al. (2014) found lower scores of executive functioning among older women, obtained using the Trail Making Test, were associated with decreased performance on the Timed Up-and-Go cognitive DT and the Fullerton Advanced Balance Scale (Muir-Hunter et al., 2014). Sullivan et al. (2009) assessed cognitive functioning using the Dementia Rating Scale, and although each score was indicative of good cognitive health, lower scores related to longer sway paths for women (Sullivan et al., 2009). Additionally, structural magnetic resonance imaging (MRI) revealed brain dysmorphology among healthy older adults was associated with increased postural sway. Brain dysmorphology included ventricular enlargement and white matter hyperintensities (WMHI), both of which contribute to weakened cognitive functioning and slower processing speed (Sullivan et al., 2009). These findings suggest that postural stability is more cognitively-involved in older adults even in the absence of fatigue. Therefore, cognitive fatigue may present an additional challenge for older adults to maintain postural stability.

7. Fall risk implications

Falls are a leading cause of injury and death among older adults (Jalali et al., 2015). A fall is an event that results in a person coming to rest inadvertently on the ground, floor, or other lower level (Kaminska et al., 2015). Both increased gait variability and increased postural sway have been shown to increase fall risk for older adults (LaRoche et al., 2014). Table A.3 presents three studies in which previous falls and/or future falls were recorded, and all studies found a relationship between cognition and fall risk among older adults. Herman et al. (2010) found that healthy older adults (no history of falls, a low comorbidity index, and good mobility upon testing) with poorer executive functioning were more likely to fall during the 2-year follow-up period (Herman et al., 2010).

Fischer et al. (2014) found that declining cognition was associated with increased falls among older adults at risk for falling (determined by physical therapists while participants performed mobility-related activities of daily living and instrumental activities of daily living) during a 1-year follow-up period (Fischer et al., 2014). Increased fall rates were associated with participants performing an increased number of risky mobility activities. Risky mobility activities were defined as activities that could lead to a fall based on his or her environment, physical, cognitive, or visual capabilities; need for assistive devices; and usual strategy or method of performance (Fischer et al., 2014). MacAulay et al. (2015) identified older adult participants as "non-fallers" or "fallers" based on fall history in the past 12 months, and found that divided attention significantly impacted spatial gait parameters (e.g. stride length) among older adult "fallers" (MacAulay et al., 2015). These findings support existing evidence that impaired cognitive functioning among older adults may cause greater instability and an increased fall risk.

8. Conclusion

Current literature discusses the impact of reduced cognitive functioning on gait and postural sway among healthy older adults. Cognitive fatigue temporarily impairs cognitive functioning, and therefore, cognitive fatigue may impact gait and postural sway during the fatigued physiological state. Cognitive fatigue may increase gait variability and increase postural sway in the same way as reduced cognitive functioning.

This literature review found that cognitive fatigue may be considered a fall risk for older adults, irrespective of their health status. Clinicians and caretakers are encouraged to practice caution when aiding a cognitively fatigued older adult during ambulation. Caretakers should especially attend to older adults that are considered a fall risk in the absence of fatigue, because fall occurrence is likely to be exacerbated when mentally tired.

Future studies should be performed to evaluate the impact of cognitive fatigue on gait and sway among healthy older adults. For example, a potential study could induce cognitive fatigue among healthy older adults using a mentally-demanding task. Gait and postural sway could be measured before and after cognitive fatigue induction to evaluate the impact of cognitive fatigue on each parameter. Multiple studies with such measurements would reveal whether or not cognitive fatigue may be considered a fall risk for older adults.

If cognitive fatigue is identified as a fall risk, various interventions could be developed to attenuate cognitive fatigue. Further strategies to reduce cognitive fatigue could be integrated into existing evidence-based fall prevention programs for older adults, which are already known to improve gait and balance (e.g. A Matter of Balance, Tai Chi, Stepping On) (Cho and Smith, 2015; Ory et al., 2015a; Ory et al., 2015b). Efforts to understand the role of cognitive fatigue could be incorporated in the Otago Education Program, a physical-therapist driven fall prevention intervention for frail older adults (Shubert et al., 2015). Such an effort could enable the impact of cognitive fatigue as a fall risk to be explored under the close supervision of a trained professional, mitigating possible injury.

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Appendix A

Table A.1
Impact of cognitive fatigue on gait.

Study	Study population	What was measured	Main findings
Dubost et al. (2006)	45 healthy older adults (65.3 ± 3.2)	Gait parameters during walking at normal and slow self-selected speeds under single and DT conditions	Under DT: decrease in mean values of stride velocity and increase in mean values and coefficients of stride time variation
Hall et al. (2011)	77 older adults (75.5 ± 5.8)	Strength, gait speed, static and dynamic balance, cognitive abilities (psychomotor and perceptual speed, recall and working memory, verbal and spatial ability, attention); time to walk while performing 4 cognitive tasks, DT costs calculated	Walking and performing a simple cognitive task explained by participant characteristics and motor factors alone; walking and performing a complex cognitive task explained additionally by cognitive factors;
Hashimoto et al. (2014)	201 elderly without dementia (67.8 ± 6.5)	Brain MRI, neuropsychological tests, gait parameters, TUG: time and number of steps under single and DT conditions	Impaired gait velocity of TUG associated with deep white matter lesions and diabetes mellitus after adjusted for age, sex, education, and cognitive function tests; impaired gait velocity of DT associated with age and score of Rivermead Behavioral Memory Test
LaRoche et al. (2014)	42 healthy men and women (50–80, separated by decade)	Cognitive function assessed with Mini-Mental State Exam (MMSE) and Trail Making Test (TMT); DT walking at self-selected speed under 3 cognitive loading conditions	Time to complete TMT positively correlated with age, stride time, and double-limb support time; subjects in 70s increased double-limb support time and stride time during most difficult DT condition
Verlindin et al. (2014)	1232 subjects from the Rotterdam Study (66.3 ± 11.8)	Cognitive and gait (7 independent domains: rhythm, variability, phases, pace, tandem, turning, base of support) assessments	Information processing speed associated with rhythm; fine motor speed with tandem; EF with pace

Previous studies investigating the impact of cognition on gait in older adults.

Table A.2
Impact of cognitive fatigue on sway.

Study	Study population	What was measured	Main findings
Sullivan et al. (2009)	28 healthy men (30–73) and 38 healthy women (34–74)	Postural stability, cognition, functional MRI	Postural instability associated with decreased cognitive functioning and brain structural dysmorphology
Van Iersel et al. (2007)	59 physically fit older adults (73.5 ± 3.4)	Balance under 3 cognitive DT conditions	Under DT balance during walking influenced directly and indirectly through decreased gait velocity
Smolders et al. (2010)	24 young adults (25.42 ± 3.55) and 23 older adults (68 ± 4.46)	Postural stability (cognitive task and 2 postural task under single and DT conditions)	More pronounced age differences in moving platform condition and further under DT condition
Granacher et	18 young adults (22.3 ±	Static postural control during bipedal stance and	Elderly participants showed larger COP displacements than young

(continued on next page)

Table A.2 (*continued*)

Study	Study population	What was measured	Main findings
al. (2011)	3.0) and 18 elderly (73.5 ± 5.5)	dynamic postural control while walking on an instrumented walkway; each with cognitive interference (CI) task and motor interference (MI) task	adults under both conditions; COP displacements increased with task complexity
Muir-Hunter et al. (2014)	24 older women (76.18 ± 16.45)	Cognition and balance (6 clinical balance tests, 4 cognitive tests, 2 measures of physical function)	Poor balance was associated with poor performance of cognitive testing of EF; association with EF strongest under DT TUG and Fullerton Advanced Balance Scale

Previous studies investigating the impact of cognition on postural sway in older adults.

Table A.3
Fall risk implications.

Study	Study population	What was measured	Main findings
Herman et al. (2010)	262 healthy and well-functioning older adults (76.3 ± 4.3)	EF using a computerized cognitive battery, other cognitive domains; gait assessment under single task and DT conditions; falls measured over 2 years	EF index predicted future falls; of the participants who reported no previous falls, those in the worst EF quartile were 3 times more likely to fall during 2 year follow-up and were more likely to transition from “non-faller” to “faller” sooner; DT gait variability predicted future falls and multiple falls
Fischer et al. (2014)	245 community-dwelling older adults (79 ± 8.0) at risk for falls	Physical, cognitive, and functional assessments; falls measured over 1 year	Declining cognition associated with an increase number of risky mobility activities and an increased rate of falls
MacAulay et al. (2015)	416 relatively healthy and cognitively intact older adults (“non-fallers” $n = 312$, 70.13 ± 6.62); “fallers” $n = 81$, 69.60 ± 6.81)	Fall history; gait characteristics (during simple and cognitive-loading walking), neuropsychological and physical test performance at 2 time points spaced a year apart	Fallers had significant alterations in spatial gait parameters compared to non-fallers during both walking tasks; shorter strides and slower step times during DT was predicted by worse executive attention/processing speed performance

Previous studies investigating the relationship between cognition and falls in older adults.

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