

Laboratory Review: The Role of Gait Analysis in Seniors' Mobility and Fall Prevention

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Key Words

Gait impairment · Gait analysis · Dual task · Attention · Motor control · Falls

Abstract

Walking is a complex motor task generally performed automatically by healthy adults. Yet, by the elderly, walking is often no longer performed automatically. Older adults require more attention for motor control while walking than younger adults. Falls, often with serious consequences, can be the result. Gait impairments are one of the biggest risk factors for falls. Several studies have identified changes in certain gait parameters as independent predictors of fall risk. Such gait changes are often too discrete to be detected by clinical observation alone. At the Basel Mobility Center, we employ the GAITRite electronic walkway system for spatial-temporal gait analysis. Although we have a large range of indications for gait analyses and several areas of clinical research, our focus is on the association between gait and cognition. Gait analysis with walking as a single-task condition alone is often insufficient to reveal underlying gait disorders present during normal, everyday activities. We use a dual-task paradigm, walking while simultaneously performing a second cognitive task, to assess the effects of divided attention on motor performance and gait control. Objective quantification of such clinically relevant gait changes is necessary to deter-

mine fall risk. Early detection of gait disorders and fall risk permits early intervention and, in the best-case scenario, fall prevention. We and others have shown that rhythmic movement training such as Jaques-Dalcroze eurhythmics, tai chi and social dancing can improve gait regularity and automaticity, thus increasing gait safety and reducing fall risk.

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Introduction

'Human walking is a risky business. Without split-second timing man would fall flat on his face; in fact with each step he takes, he teeters on the edge of catastrophe', the British anthropologist John Napier remarked [1]. In order to propel ourselves forward, we have to almost throw ourselves off balance with each step we take. Mastering this balancing act takes most of our childhood years [2]. By adulthood, the complex motor task of walking occurs automatically. However, in the elderly, walking is often no longer an automaticity. Older adults require more attention for motor control while walking than younger adults [3–5]. Falls, often with serious injurious and/or psychosocial consequences, can be the result.

This paper addresses the role of spatial-temporal gait analysis in assessing the mobility and falls of seniors.

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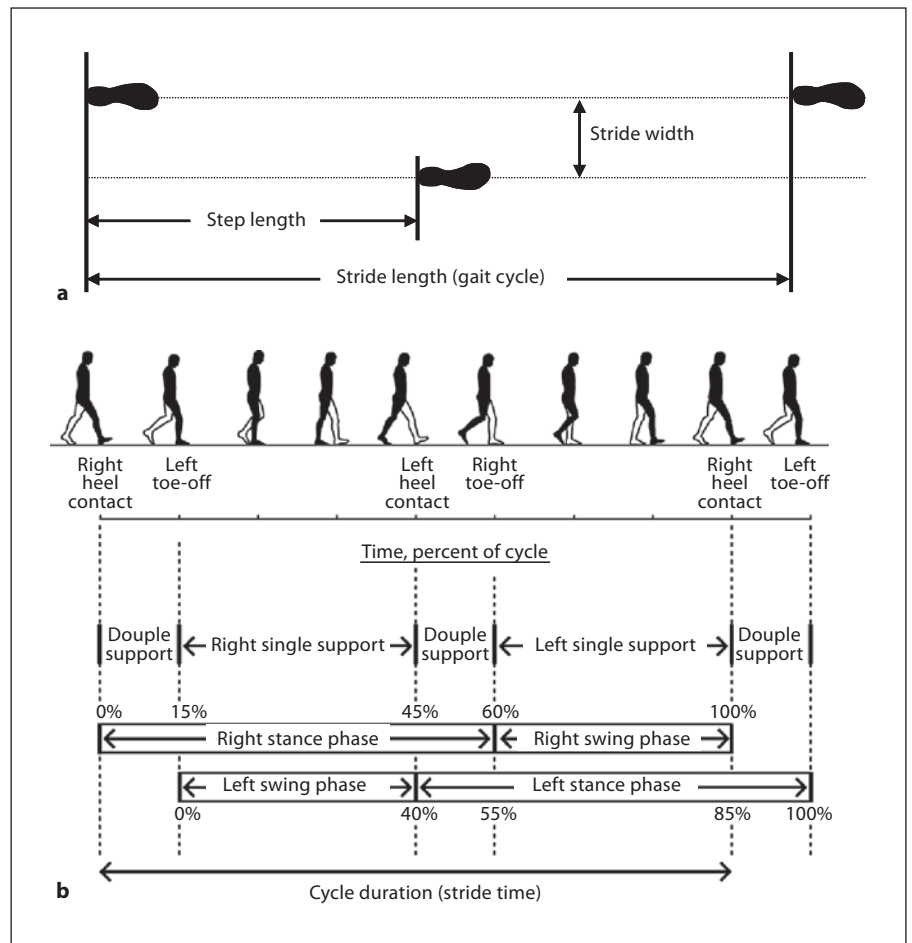


Fig. 1. a Spatial gait parameters. **b** Temporal gait parameters.

When gait is no longer completely automatic, other tasks performed while walking can lead to gait disturbances and even falls. Dual-task paradigms of gait analysis for cognitive stress resistance testing and for examining the association between divided attention and motor control are discussed. Detection of such gait disorders allows the timely introduction of individually tailored interventions targeted at improving gait regularity, automaticity and thus also gait safety. Examples of such evidence-based intervention programs are introduced.

Gait in Healthy Seniors

In order to appreciate detrimental gait changes that may lead to falls, it is beneficial to be familiar with some of the gait changes that accompany normal, healthy aging. David Winter was one of the first to compare gait parameters of healthy older (mean age: 68 years) and young

(mean age: 25 years) adults [6]. His study showed that the cadence was the same in both groups. Yet, compared to the young adults, the older adults had significantly reduced gait speed, decreased stride length and increased double support time (fig. 1). The toe push-off was less vigorous. Horizontal heel contact velocity was also significantly higher. Menz et al. [7] later reported a reduced gait speed, decreased step length and increased step timing variability in older healthy adults (mean age: 79 years) compared to young adults (mean age: 29 years). These changes represent either a degeneration of the balance control system or compensatory adaptations providing safer gait.

Gait, Falls and Fall Prediction in Seniors

Falling is classified as one of several geriatric syndromes. Defining features of geriatric syndromes includes the contribution of multiple risk factors and the

presence of chronic predisposing diseases and impairments in one or more systems (such as sensory, central and peripheral nervous, cardiopulmonary and musculoskeletal) that render an older person vulnerable to situational challenges [8, 9]. Falls are the leading cause of unintentional injury and hospitalization in people aged 65 years and older [10]. One in 3 adults in that age group falls each year [11–13]. Of those, 20–30% suffer moderate-to-severe injuries that make it hard for them to get around or live independently and increase their risk of an early death [11, 14, 15]. The 12-month risk of mortality after being hospitalized for a fall is approximately 50% [16]. Falling without serious injury increases the risk of skilled nursing facility placement 3-fold after accounting for cognitive, psychological, social, functional and medical factors; a serious fall injury increases the risk 10-fold [9]. Many people who fall, even those who are not injured, develop a fear of falling. This may cause them to limit their activities, leading to reduced mobility and physical fitness and increasing their risk of falling [11, 17]. In a systematic review of 33 studies on community-dwelling older adults performed by Tinetti and Kumar [9], the strongest risk factors for falling include previous falls as well as strength, gait and balance impairments. In one study from that systematic review, the 1-year risk of falling increased from 8 to 19 to 32 to 60 to 78% (χ^2 test for order in proportions: 62.7; $p < 0.001$) as the number of risk factors increased from 0 to 4 or more.

Although the causes of falls are often multifactorial, there is one common feature: the majority occur during walking [6, 7, 18]. Several studies have identified changes in certain spatial and temporal gait parameters as independent predictors of fall risk. Maki [19] observed that increased stride-to-stride variability in stride length, stride speed and double support time as well as increased stride width were predictive of falls in the ensuing 6 months for residents of a senior living facility (living independently in apartments, no walking aids; mean age: 82 years). These results were confirmed by Hausdorff et al. [20], who established a strongly predictive positive correlation between increased stride-to-stride variability in cycle time and falls in the 12-month follow-up period for community-dwelling seniors aged 70 years and older. They also reported that quantitative measures of gait variability may be more sensitive measures of gait than more conventional parameters such as gait speed and cadence. Several years later, Hausdorff et al. [13] confirmed that both stride time and swing time variability were fall predictors in community-dwelling elderly, and reported

Table 1. Specifications of GAITRite electronic walkway system used at Basel Mobility Center

Length	972 cm
Width	61 cm
Number of pressure sensors	29,952
Walkway model	Platinum
Software version	39
Scanning frequency	60 Hz
Length of extensions at each end of walkway ¹	125 cm

¹ Optically similar to the walkway; yet, nonactive extensions capture initial acceleration and terminal deceleration, so that gait measurements are obtained in steady-state walking conditions.

the feasibility of obtaining measurements of gait variability in a clinical setting.

Such gait changes are very often too small to be detected by clinical observation alone. For example, Maki [19] showed that an increase in stride length variability of just 1.7 cm had an odds ratio for falling of 1.95 (95% confidence interval). Yet, the clinical consequences of such subtle changes can be immense. Therefore, precise, objective gait analysis is necessary to quantify gait changes and to identify fall risk.

Gait Analysis to Assess Fall Risk

In the past, measurements of spatial-temporal gait parameters were performed manually and were thus labor and time intensive. Methods ranged from absorbent paper to record wet footprint placement [21] over talcum powder dusted on the plantar surface of the foot [22] to ink-saturated felt pads glued to foot switches [19]. Current systems allow relatively simple, fast and objective gait analysis. Available assessment tools include optoelectronic systems (e.g. Vicon Motion Systems, Los Angeles, Calif., USA), force platforms (e.g. Kistler Corp., Winterthur, Switzerland), shoe-integrated wireless sensor systems (e.g. Stride Analyzer; B&L Engineering, Tustin, Calif., USA), accelerometers (e.g. DynaPort MiniMod; McRoberts Moving Technology, The Hague, The Netherlands), angular velocity transducer systems (e.g. Sway-Star; Balance International Innovations GmbH, Iseltwald, Switzerland) and electronic walkways with integrated pressure sensors (e.g. GAITRite; CIR Systems, Havertown, Pa., USA). Which system is best depends on the research and clinical questions addressed.

At the Basel Mobility Center, we employ the GAITRite electronic walkway system for spatial-temporal gait measures since our focus is on clinically relevant, functional and dynamic gait analysis. The specifications of the system we use can be found in table 1. The system is simple and fast, both for the participants and the test administrators. The testing environment is bright, quiet, open and nonintimidating. Participants wear their normal clothes, their normal shoes and use their walking aid if they have one. With the exception of a safety belt, they are not attached to any devices which could interfere with their normal gait. All gait analyses are performed according to the European guidelines for spatial-temporal gait analysis to provide valid, reliable and comparable data [23].

Gait Analysis at Basel Mobility Center

The Basel Mobility Center is integrated into a university hospital setting. We have a set clinical routine with both in- and outpatients as well as clinical research. The indications for functional gait analysis range from assessment of falls or fall risk to providing a diagnostic tool for neurologists and neurosurgeons for their patients with normal pressure hydrocephalus. However, our main focus is gait and cognition. A large part of our clinical routine consists of outpatients from our Memory Clinic, whereby gait analysis is part of the medical examination of those patients.

Routinely, our patients and study participants perform 5 different walks (1 trial each) during one 20-min gait analysis session. Three of those are single tasks: normal (self-chosen pace), slow ('slower than normal') and fast ('as fast as possible') walking. Normal walking provides us with baseline information about their mobility. The performance while walking slowly can provide insight into mediolateral stability. The difference between normal and fast walking provides information about their functional reserve. Also, measuring gait at all 3 speeds allows the normalization of certain gait parameters [24]. Then 2 dual tasks are performed, a working memory task – walking and simultaneously counting backwards from 50 by steps of 2 out loud – and a verbal fluency task – walking and simultaneously enumerating animals out loud. Participants are instructed to perform both tasks simultaneously, no task prioritization is given. Before going into any further discussion, the following is an example from our Mobility Center.

Brief Case Report

A 72-year-old, community-dwelling, independently ambulating female was referred to our Mobility Center because of recurrent falls. Several outpatient diagnostic tests had failed to reveal the etiology of the falls (Holter electrocardiography, 24-hour blood pressure monitoring, electromyography, electroencephalography, Doppler and duplex sonography of the extra- and intracranial vessels). Gross medical and neurological examinations as well as the patient history, except for falls, were unremarkable. Walking as a single task in all 3 tempi was also unremarkable. During normal walking, her gait speed was 123 cm/s and her gait cycle time variability was 1% (online suppl. video 1; for all online suppl. material, see www.karger.com/doi/10.1159/000322194; our reference normal values are a spontaneous gait speed of >100 cm/s, and a gait cycle time variability of <3%). Had our gait analysis stopped here, we would have reported her gait as normal. Yet, walking under the above-described dual-task conditions revealed a considerable gait disorder. For example, during the working memory task, her velocity decreased to 24 cm/s and her gait cycle time variability increased to 74% (online suppl. video 2). During that walk, she stopped several times (accounting in part for the low speed and the high cycle time variability) and even almost fell laterally after teetering on one foot for several seconds. Surprisingly, she was unaware of those events. Indeed, after the walk, her only comments reflected her frustration with not producing more numbers while counting backwards. Neuropsychological testing at our Memory Clinic revealed the diagnosis of mild cognitive impairment with deficits in attention and executive function. We concluded that the mild cognitive impairment and executive dysfunction were responsible for her gait disorder under dual-task conditions as well as for her recurrent falls.

Dual-Task Paradigm for Cognitive Stress Resistance Testing

How can the marked discrepancy between unremarkable gait while walking only and such a gait disorder while walking as part of a dual-task situation be explained? In 1997, Lundin-Olsson et al. [25] showed in a landmark paper that 'stops walking when talking' is associated with an increased fall risk. That observation drew attention to the importance of the association between gait and cognition as well as the clinical significance of dual-task testing paradigms.

As previously mentioned, walking is a complex motor task, yet generally performed automatically by healthy adults. The attentional demands are therefore minimal. In older adults, age-related neuromotor changes such as reduced motor strength or decreased sensory input (vision, hearing, proprioception) increase the attentional demands needed for walking. This increased demand is met at the cost of a reduction in the central processing capacity for attentional reserve [26].

Yet by so doing, these deficits can be compensated, so that simple routine activities of daily living or spatial-temporal assessment of normal walking alone remain unremarkable, as seen in online supplementary video 1. However, rarely in normal everyday life do we only walk. Usually, we are doing something concomitantly, such as talking on a mobile phone or carrying a cup of coffee. Simultaneously performing another task (cognitive or motor) while walking is a dual-task situation, and this raises the bar on attentional demands. If the demands on attention cannot be met by the attentional reserve capacity available, then performance in one or both tasks is impaired (online suppl. video 2) [3, 27, 28].

This concept of divided attention is the basis of our Basel Assessment Model by using gait analysis in dual-task conditions to assess mobility and fall risk. The dual-task paradigm examines the effect of a simultaneously performed cognitive task on gait [27, 29–33]. It is important to remember that no prioritization is given in the task instructions. The allocation of attentional resources is, consciously or subconsciously, self-chosen, as is the case with normal activities of daily living. In accordance with the capacity sharing theory, if attentional demand exceeds the available attentional resource capacity, performance in one or both tasks will be impaired [26, 29]. This impaired performance is referred to as ‘dual-task interference’.

The dual-task paradigm can also be thought of as a cognitive stress resistance model because it challenges the attentional reserve available. The threshold for the occurrence and extent of dual-task-related gait interference is dependent upon the cognitive load. If the cognitive load is great enough – due to the task itself or the task complexity –, the threshold will at some point be crossed and not enough attentional reserve can be drawn from the central capacity to meet the attentional demands. This has also been described as a ‘dose-response’ relationship, whereby the more demanding the secondary, attention-splitting task, the greater the gait disturbance [3, 5, 34, 35]. When the secondary task is demanding enough, even young, healthy adults will show dual-task-related gait interference [35].

The dual-task paradigm allows the assessment of the effects of divided attention on motor performance. It also permits detection not only of gait deficits, which under the single-task condition of walking alone may otherwise go unnoticed, but also of possible cognitive deficits. A main advantage, of course, is that such deficits can be detected at an early stage, allowing early intervention and, in the best-case scenario, prevention. When dual-task in-

terference and gait instability are detected, the goal is to provide measures to stabilize gait before a fall or functional dependence occurs. For a better understanding of when this may be the case, it is important to know which and what type of detrimental gait changes under dual-task conditions are associated with an increased risk of falling.

Dual-Task-Related Gait Changes as a New Surrogate Marker for Fall Risk

Gait analysis with walking as a single-task condition alone is often insufficient to reveal underlying gait disorders present during normal, everyday activities. Not all gait disorders under dual-task situations are as obvious and visible to the naked eye as can be seen in the videos from our brief case report. As previously mentioned, because these changes are usually not detectable by clinical observation alone, objective quantifications of these clinically relevant gait changes are necessary to determine fall risk.

Beauchet et al. [36] were among the first to demonstrate that performing the attention-splitting dual task of walking forward at a self-chosen pace while simultaneously counting backwards out loud increased stride-to-stride variability in both stride length and stride time in older adults (mean age: 83 years), whereas no significant change in gait variability was found in young adults (mean age: 22 years).

Previous reports describe an association between dual-task-related gait changes and fall risk among the elderly [25, 37]. Beauchet et al. [38] investigated whether the type of spoken task performed while walking made a difference in inducing gait interference in transitionally frail older adults (mean age: 83 years). Spatiotemporal gait parameters were measured while walking alone, or while simultaneously performing either an arithmetic task (counting backwards from 50) or a verbal fluency task (enumerating animals). It had previously been suggested [39] that similar gait changes occurred under dual-task conditions regardless of the type of task performed while walking. Beauchet et al. [38] found that, indeed, compared to normal walking (i.e. self-chosen pace), the gait speed decreased and cadence increased under both dual-task conditions with no significant difference between the two dual-task conditions. However, lateral gait instability increased significantly only with the arithmetic, but not with the verbal fluency task.

Extending the knowledge that increased gait variability in elderly community dwellers is associated with a high risk of falling in the ensuing 6–12 months [13, 19, 20], Kressig et al. [40] reported that this association is also valid for independently walking patients of an acute care geriatric hospital ward. Increased stride time variability under a dual-task condition (counting backwards out loud while walking) retrospectively identified more fallers during the 20- to 30-day hospital stay than did increased stride time variability while walking alone. Moreover, a critical threshold for the stride time coefficient of variation [(standard deviation/mean) × 100] of >10% under the dual-task condition was strongly associated with falls.

In further investigations into dual-task-related gait changes and fall risk, Beauchet et al. [41] examined not only changes in gait but also in performance of the spoken task (counting backwards) while walking, compared to the same test performed while seated. Surprisingly and interestingly, they found that those healthy older adults (mean age: 85 years) whose counting performance was better while walking than while seated had a higher fall rate over the next year than those whose counting performance was better while seated. The authors hypothesized two explanations for the improved counting performance while walking. Firstly, both tasks, counting and walking, have rhythmic components which, in a described ‘magnet effect’ [42] attract each other. Thus, as an additive effect, counting performance increased while walking in the group of fallers. Secondly, task similarity (rhythmic components of both tasks) may reduce attention interference, leading to better cognitive performance. It is thus possible that the fallers in the study had an irregular gait while walking alone. By combining the rhythmic tasks of walking and counting backwards, those participants may not only have improved their cognitive performance but enhanced their gait regularity as well.

Interventions to Improve Gait Regularity, Automaticity and Gait Safety

The ability to beneficially couple two rhythmic tasks to improve gait was reported by Kressig et al. [43]. Regular, long-term practice of Jaques-Dalcroze eurhythmics (JDE), consisting of multitask exercises requiring high levels of attention, memory and coordination performed to the rhythm of improvised piano music, may prevent age-related increases in gait variability under dual-task conditions. In this pilot study, 10 women (mean age: 80 years) who had

regularly practiced JDE for more than 40 years were compared to a control group of similar adults with no regular exercise routine. Gait was measured during normal, self-paced walking and during the dual-task condition of walking forward at their normal pace while counting backwards out loud. The control group significantly increased their gait variability during the dual task (11.9 compared to 3.9% during normal walking), whereas gait variability in the JDE group remained unchanged compared to normal walking alone (2.7 and 2.1%, respectively) [43].

In a randomized controlled study over 6 months, Trombetti [44] demonstrated a reduction in gait variability and in fall risk in community-dwelling men and women with no previous JDE experience (data not yet published, reprinted by permission of Dr. Trombetti). Sixty-six participants in the JDE intervention group (mean age: 75 years) participated in a weekly 1-hour JDE class. After the 6-month intervention period, the JDE group, compared to the control group and baseline gait values, significantly improved their gait variability (step and stride length variability) under an arithmetic dual-task condition (walking forward at their normal pace while counting backwards). Additionally, the postintervention fall risk in the JDE group was lower than that in the controls.

Verghese [45] reported that long-term social dancing may be associated with better gait in community-dwelling older men and women. Gait was quantitatively measured in 24 long-term social dancers (mean age: 80 years; mean duration of dancing: 36.5 years) and 84 age-, gender- and education-matched nondancers. There were no significant group differences in the frequency of participation in other cognitive and physical leisure activities. The social dancers walked faster (100.5 compared to 87.2 cm/s) by taking longer steps (58.6 vs. 52.3 cm) and strides (117.8 vs. 103.4 cm) than the nondancers. Also, the stance phase was decreased (63.9 vs. 65.9%) and the swing phase was increased (36.1 vs. 34.1%), reflecting a more stable gait pattern [45].

A different type of exercise intervention reported to improve gait safety is tai chi. Tai chi involves increasingly difficult, slow, graceful movements over a progressively diminishing base of support, which challenges balance and facilitates concentration on the body position [46, 47]. Wolf et al. [47] reported interesting effects of tai chi training in community-dwelling seniors (mean age: 76 years). Their study consisted of three trial arms: weekly training in either tai chi or in computerized balance training with visual feedback on the center of pressure, or a nonexercising educational control group which met weekly to discuss topics of health interest with a gerontological nurse/researcher. Outcome variables included

biomedical measures such as strength and flexibility; however, no gait analyses were performed. Fear of falling was assessed by the Falls Efficacy Scale [48]. Falls were ascertained by a monthly calendar with fall information or by monthly phone calls by the project staff. Wolf et al. [47] reported that, although no effect on balance was found, 15-week tai chi participation resulted in a 47% reduction in fall risk (relative risk: 1.417; $p = 0.0002$; risk score resulting from adjusted estimates from the Anderson-Gill extension of the Cox proportional hazards model). Additionally, there was a significant reduction in the fear of falling in the tai chi group compared to the education group ($p = 0.046$ for pre- vs. postintervention fear of falling scores) [47]. Just as interesting, almost half of the participants continued tai chi training after the study [46, 47], which underscores the importance of fun and positive social aspects of sustainable interventions [46].

In a pilot study by Bridenbaugh and Kressig, the effects of a 10-week tai chi intervention on gait stability in transitionally frail older adults were investigated (unpublished data). Due to the small sample size, the results were not significant, yet suggested improved gait stability. Compared to baseline values, stride time variability decreased under both an arithmetic working memory dual task and a verbal fluency dual task (enumerating animals).

A common feature of all interventions discussed thus far is rhythm. Rhythmicity is an essential element of movement and integral to many motor control functions [49, 50]. Hayden et al. [50] reported that rhythmic-auditory-stimulation (RAS)-enhanced gait training improved gait in patients hospitalized for a stroke. Two styles of music were digitally mastered to provide a certain number of pronounced, but not accented, beats per minute. The cadence of the RAS beats was matched to the initial cadence of the participants and progressively increased. All participants received 30 daily conventional physical therapy sessions. RAS was incorporated into the training in 10, 20 or all 30 sessions. Gait measures (derived from a 10- to 15-meter walk after counting steps and timing the duration) were assessed 4 times throughout the 30-day period. Independent of the number of RAS-incorporating sessions (10, 20 or 30), significant improvement was shown in cadence, velocity and stride length (baseline vs. 4th gait measures). In the group with 10 RAS sessions, the cadence improved by 25.4% (from 81.210 to 101.850 steps/min), velocity improved by 59.2% (from 30.170 to 48.020 cm/s) and stride length improved by 57.6% (from 0.594 to 0.936 m). In the group with 20 RAS sessions, the cadence improved by 135.2% (from 28.554 to 67.164 steps/min), velocity improved by 183.6% (from

12.970 to 36.788 cm/s) and stride length improved by 105.3% (from 0.452 to 0.928 m). In the group with 30 RAS sessions, the cadence improved by 51.3% (from 74.598 to 112.840 steps/min), velocity improved by 182.6% (from 28.920 to 81.728 cm/s) and stride length improved by 99.7% (from 0.720 to 1.438 m) [50].

These intervention strategies all aimed to improve gait via cadenced, rhythmic movement training. The improved gait parameters, particularly those while dual-tasking, may represent a beneficial coupling of two rhythmic tasks, as previously mentioned. Another explanation may be that the high level of attention needed for the aforementioned multitasking movement exercises improves gait automaticity, thereby reducing attentional demands and minimizing the interference of a simultaneously performed cognitive dual task with gait [43].

An additional or alternative approach for individuals with cognitive deficits focuses on stabilizing gait by improving cognitive function [29]. It is known that acetylcholine esterase inhibitors (e.g. galantamine) can improve attention and executive function in individuals with Alzheimer's disease, and that attention and executive function are necessary for motor control. Assal et al. [51] recently reported that dual-task-related gait performance (stride time) in 9 individuals with Alzheimer's disease (mean age: 77.9 years) significantly improved after 6 months of treatment with galantamine. The stride time was significantly longer under the dual-task condition of walking while counting backwards out loud (1,499.1 ms) than while walking alone as a single task (1,122.6 ms) before treatment ($p = 0.01$), but not after treatment (stride time under dual task of 1,278.5 ms vs. 1,166.1 ms while walking alone; $p = 0.09$). The increased stride time before treatment with galantamine is a marker for an inability to appropriately adapt the allocation of attention between gait and the walking-associated dual task, resulting in an increased fall risk. The absence of a significant increase in stride time while dual-tasking after treatment suggests a galantamine-facilitated improvement in the neuromotor control of gait, providing a safer, more stable gait under a dual-task condition [51].

Conclusion

Walking is indeed a 'risky business', as John Napier noted [1]. When gait in older adults is no longer an automaticity, gait deficits and even falls can occur in dual- or multi-task conditions of everyday activities. Spatial-temporal gait analysis, particularly under dual-task conditions, can

detect discrete gait disorders which are not perceptible to the naked eye. Several dual-task-related gait changes have been identified as fall predictors. Early detection allows early intervention. The literature supports that rhythmic movement interventions such as JDE, tai chi and social dancing can improve gait regularity and automaticity, thereby increasing gait safety and reducing fall risk.

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