REVIEW

Different protocols for analyzing behavior and adaptability in obstacle crossing in Parkinson's disease

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Abstract: Imbalance and tripping over obstacles as a result of altered gait in older adults, especially in patients with Parkinson's disease (PD), are one of the most common causes of falls. During obstacle crossing, patients with PD modify their behavior in order to decrease the mechanical demands and enhance dynamic stability. Various descriptions of dynamic traits of gait that have been collected over longer periods, probably better synthesize the underlying structure and pattern of fluctuations in gait and can be more sensitive markers of aging or early neurological dysfunction and increased risk of falls. This confirmation challenges the clinimetric of different protocols and paradigms used for gait analysis up till now, in particular when analyzing obstacle crossing. The authors here present a critical review of current knowledge concerning the interplay between the cognition and gait in aging and PD, emphasizing the differences in gait behavior and adaptability while walking over different and challenging obstacle paradigms, and the implications of obstacle negotiation as a predictor of falls. Some evidence concerning the effectiveness of future rehabilitation protocols on reviving obstacle crossing behavior by trial and error relearning, taking advantage of dual-task paradigms, physical exercise, and virtual reality have been put forward in this article.

Keywords: gait, obstacle crossing, cognition, behavior, Parkinson's disease, aging, falls

Introduction
Postural control
Postural balance is a complex task performed by the central nervous system (CNS), which involves feedback integration of multiple sensory inputs, including those from the vestibular, auditory, visual, and motor systems, based on an internal body schema.[1] Postural control is an essential pillar for independent gait, in coordination with locomotion generators, establishing, and maintaining the proper postural orientation of body parts relative to one another and within the limits of biomechanical constraints inherent to the person and to the task and environment, and also ensuring the dynamic stability of the moving body (Figure 1).[2,3] According to Schoneburg et al,[4] the dynamic postural control during locomotion can be characterized by the integration of the 4 main postural control domains: 1) balance during quiet stance; 2) reactive postural adjustments to external perturbations; 3) anticipatory postural adjustments (APAs) in preparation for voluntary movements; and 4) dynamic balance during the movements, such as gait. One of the most concerning features of several neurodegenerative diseases is postural instability, which increases the risk of falls.[5] In fact, postural instability is one of the disabling symptoms of Parkinson's disease (PD), with falls occurring in 46% people,

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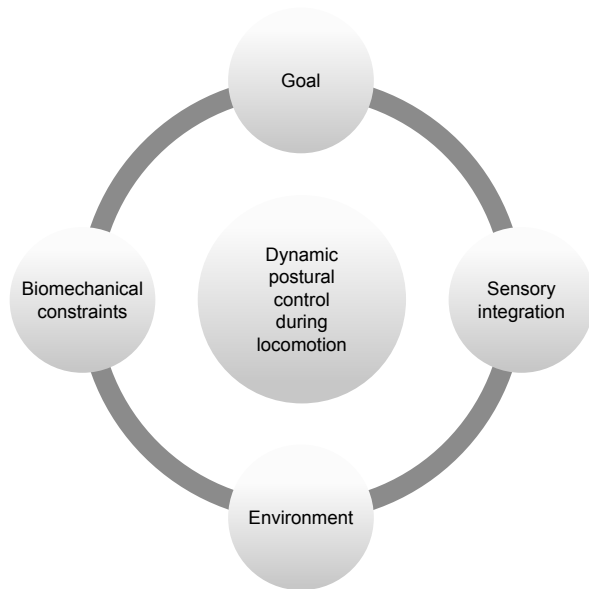Email miguelgago@hospitaldeguimaraes.min-saude.pt

Figure 1 The model describing the elements that affect dynamic postural control during locomotion.
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in a given period of 3-months.[6] As such, preserving gait is fundamental in PD, where independent gait is threatened by falls and multisystem deconditioning, thus requiring lifestyle and behavioral changes that warrant sustained and constant physical activity and exercise.[7]

Obstacle crossing

Crossing obstacles is a common challenge encountered in everyday life, where the human body has to adjust the visual perception as well as the length and height of each step to avoid contact in order to calculate how to pass the obstacle properly. The limitations in gait adaptability might be one of the reasons that put the elderly people at a greater risk of tripping and falling when crossing obstacles under time-constrained conditions.[8] A recent within-group comparison by Caetano et al[8] has shown that young individuals maintain the same walking pattern for both the baseline and walk-through conditions, whereas older adults reduce their step length, step velocity, and increase their double-support time significantly in walk-through conditions. As compared with their younger counterparts, the older adults demonstrate a more conservative adaptation strategy, exhibit poorer stepping accuracy, and make more stepping errors. As such, the authors concluded that reduced gait adaptability might place older adults at an increased risk of falling when accomplishing unexpected hazards.[8] Stegemöller et al[9] have also shown that PD patients change their behavior when crossing an obstacle, opting for a more conservative strategy,

including a reduction in the mechanical demands and increase in dynamic stability during obstacle avoidance tasks. Galna et al[10] have shown that PD patients inadvertently increase their step width when crossing an obstacle, as a compensation strategy, rather than increasing foot height as seen in healthy subjects. PD patients do not place their foot close enough to the front of the obstacle, as compensation for their reduced step length, being, therefore, more likely to step over on the obstacle while crossing it. In fact, the ability to make adjustments in gait to safely clear obstacles at home and in the community, like in rugs, shower recesses, and roadside curbs, is compromised in PD.[10]

Risk of falling

Elements attributed to an individual's risk of falling are commonly evaluated at 3 levels: 1) intrinsic factors, occurring at the level of the individual; 2) extrinsic factors, occurring at the level of the environment; and 3) activity-related factors. Falls are one of the most serious and common medical issues affecting the older adults. Indeed, many of the consequences of falls are psychological, including the fear of falls. There is a growing body of evidence that suggests the fear of falls may elicit a self-behavior and mind state that auto-perpetuates the state of risk of falling, by reducing physical and functional activity.[11] Pan et al[12] investigated the mechanics of obstacle crossing in older adults that have been classified as having low or high risk of falling in accordance with having a score higher or inferior to the cut-off of 36 on the Tinetti Balance and Gait scale, respectively. The kinematics of the leading and trailing leg was evaluated when crossing an obstacle with different heights of 10%, 20%, and 30% of leg length. Increasing the height of the obstacle led to increased toe-obstacle distance, and shortened swing phase of the leading limb, with a greater adaptation of clearance height of the trailing leg. Adults at a higher risk of falling exhibited a greater toe-obstacle clearance of the leading leg, the lesser symmetry between the leading and trailing legs, and a narrower step width. As such, according to this study, this gait behavior and obstacle crossing adaptability, may be associated with an increased likelihood of tripping and falling.[12]

Motor and cognitive rehabilitation

There is increasing evidence that motor rehabilitation can be employed to improve a safer obstacle-crossing behavior. In the last few years, there has been a growing body of scientific research where rehabilitation has been merged with new technologies. Caetano et al[13] appraised the influence of home-based interactive video game step training on

gait analysis performance in PD patients. Gait adaptability performance was evaluated at baseline and 12 weeks of follow-up, using different challenging obstacle paradigms (obstacle avoidance, short stepping target, long stepping target and no target/obstacle). According to this study, a home-based interactive step training was able to improve gait adaptability in response to unpredictable stepping targets in PD patients. Liao et al[14] examined the effects of virtual reality-based exercise on obstacle-crossing performance and dynamic balance in individuals with PD. Compared with a traditional group, the virtual reality-based Wii Fit exercise, as part of a multifaceted training intervention was effective in improving obstacle-crossing performance, dynamic balance, functional ability, and the quality of life in PD patients. During the daily life challenges of crossing obstacles, besides the visual context and inputs coming from the environment, auditory inputs have also been shown to provide meaningful spatial cues or, in contrast, constitute contra-productive information.[15,16] There is already substantial evidence that auditory cues, especially rhythmic auditory cues with action relevance (motor and sensorial relevance) (eg, wearing the sound of the steps in the gravel), improves gait in PD.[17] Still, there is lacking information concerning the effect of auditory cues during obstacle crossing and/or gait adaptability. Pestana et al[18] investigated the effect of auditory cues on gait asymmetry in patients with PD compared with that in healthy subjects in an unobstructed environment and in an environment with an obstacle. It was found that auditory cues decreased gait asymmetry in PD in an unobstructed environment; they failed to provide any benefit during obstacle crossing, showing no significant effect on the asymmetry of gait in PD. The aforementioned studies support the concept that, in addition to muscle strengthening, the cognition and adaptability of behaviors of gait during obstacle crossing are also possible and clearly warrant further investigation. It can thus be further hypothesized that by trial and error learning mechanisms, even when neuropathology has disturbed spinal and supraspinal automatic neural network involved in postural control and locomotion, the crossing behavior can be revived and relearned in order to achieve a new and better outcome.

In the backdrop of the aforementioned context, the objectives of this paper are to provide a critical review concerning 1) different gait analysis measures and respective clinometric properties, regarding clinical progression and treatment outcomes; 2) the interplay between cognition and gait and how different apparatus and paradigms can be used to study different domains in gait and postural control;

3) and ultimately how obstacle-crossing behavior adaptability may be compromised in patients with PD, putting forward potential translational physiotherapy opportunities.

Clinimetric properties of gait analysis

Three-dimensional kinematic measures of gait are used in clinical gait analysis,[19] and still, continues to be the gold-standard critical measure for gait research and clinical practice. However, it requires highly specialized staff to run these systems; their high cost and long preparation time are hurdles to their wholesale adoption as quotidian clinical tools. In the last decade, body-worn sensors have been proven to be an alternative tool for motion analysis, with growing applications in movement disorders, particularly in the analysis of posture, balance, and gait in PD.[20] The measurements of gait can be aggregated into 2 group domains, including 1) spatiotemporal characteristics that demonstrate a typical cycle, described as the mean of multiple steps; and 2) dynamic trait of gait that expresses the inconsistency of spatiotemporal measures across multiple steps.[21] The spatiotemporal characteristics of gait are a reliable and valid measurement for healthy controls who are aging and also for inferring deviation from normality and diagnosing neurodegenerative diseases.[22] Gait speed is the most commonly used spatiotemporal gait parameter owing to its simplicity and extensive historic backup research. It is primarily considered as the primary outcome in gait rehabilitation clinical studies.[23] Yet, though gait speed may be the absolute reflection of the overall global gait performance, it does not reveal the fundamental debilitations (eg, reduced step length and step width) or the underlying pathology that is affecting the performance.[24] Gait variability, reflecting the dynamic trait of gait, has been presented as an alternative variable, showing good correlation with the impairment of gait along with clinical progression and severity of the disease.[21] Several descriptions of the dynamic traits of gait, collected over long periods, may unravel the structure and pattern of fluctuations in gait and underlying pathology. Certainly, gait variability and fractal scaling of gait break down with age and hence may be sensitive markers of early dysfunction in PD.[25] In fact, both coordination and consistency can be combined into a single element of gait performance.[3] However, in a systematic review concerning the therapeutic interventions and rehabilitation in aged adults and gait variability assessment, several critical issues have been highlighted; and a large number of variability outcome variables have already been published without a consensus for robust estimates.[26] The discriminative and predictive validity of gait variability

has been inferred, using principal components of factor statistical analysis, from cross-sectional and longitudinal studies rather than being formally examined.[27] A study by Brach et al provided point estimates of meaningful change for swing time and stance time variability in 241 community-dwelling older adults based on 2 annual follow-up analyses, although CIs were not reported.[28] The measurement of gait dynamics (gait variability) has already been proposed as an outcome measurement in pharmacological clinical trials, particularly in assessing the benefit of donepezil in reducing the risk of falls in older people with mild cognitive impairment.[29] However, given the concerns regarding the reliability of different sensors and assessment of gait by different protocols and different environments, the assumption of the variability of one particular gait parameter as the ultimate and final answer is too early. Hence, continued development of robust and practical protocols and accessible processing techniques is paramount to help us understand the contribution of gait dynamics and the pretense of its use as an outcome measurement in clinical trials better.

Interplay between cognition and gait

Over the past decade, several studies have emphasized on the interplay between balance, gait, and risk of falls on the one hand, and cognitive function and risk of dementia on the other hand.[30] Cognitive deficits deteriorate with aging and may even cause gait impairment, increasing the risk of falls, particularly during more challenging situations. Nearly 60% of elderly people with cognitive impairment fall every year, which is 2-fold more than that observed among their cognitively intact peers. Figure 2, extracted from a study by Amboni et al,[31] properly depicts the coexistence of cognitive impairment and gait abnormalities, as well as dementia and increased risk of falls. Conversely, there is a growing body of data showing that gait abnormalities may predict the future development of dementia and that cognitive impairment increases the risk of falls.[31] The executive function refers to a set of higher order cognitive processes that control, integrate, organize, and maintain other cognitive abilities. It appears that the dorsolateral prefrontal cortex, a structure of the brain that is associated with executive function and attention, is also associated with several gait domains, which further highlights the relationship between cognition and gait, and the effect of interventions enhancing executive function.[32]

Another group of researchers suggests that cognitive interventions may have a carry-over effect from cognitive to physical gait domains, thus providing a dual beneficial effect, reducing dual-task costs and the risk of falling. A study by
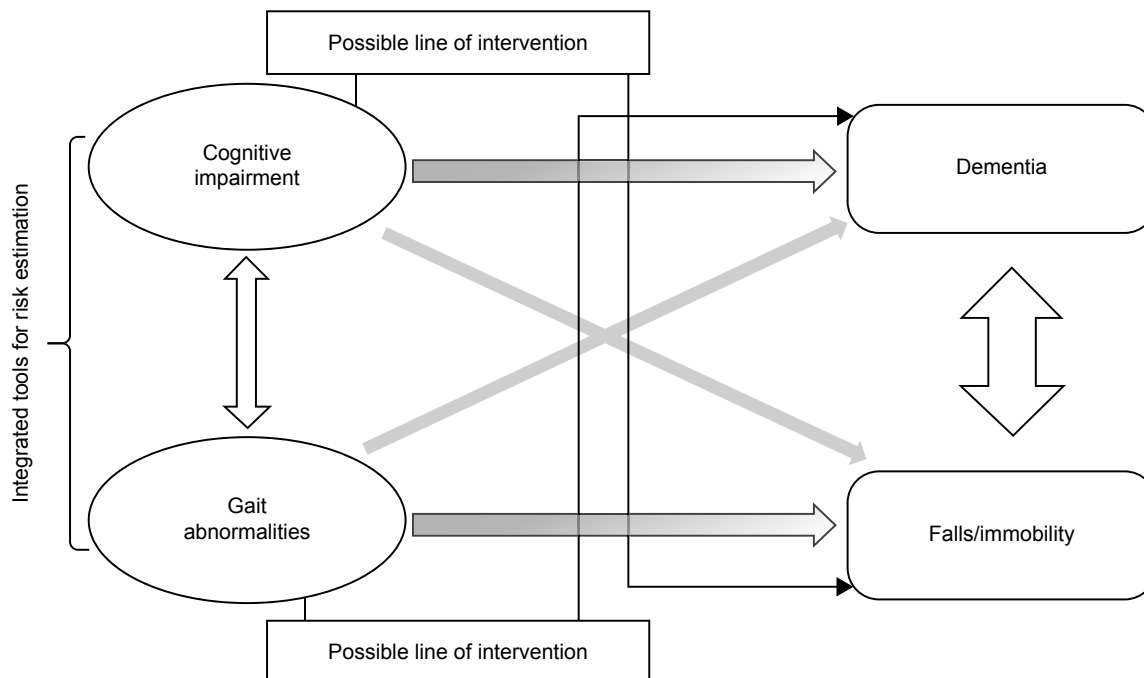

Figure 2 Cognitive impairment predicted dementia, although gait abnormalities increased the risk for falling (shaded arrows).
Notes: A complete understanding suggests that cognitive impairment and gait abnormalities, coupled with dementia and falls, are related to each other (white arrows). In the light of recent evidence, gait abnormalities predict dementia and cognitive impairment raises fall risk (gray arrows); based on the close relationship between cognition and gait on the one hand, integrated tools for risk estimation are needed (bracket). Furthermore, the possible lines of intervention (black arrows) could rely on increasing cognition for fall prevention and on walking training for lessening dementia risk. Copyright © 2013. John Wiley and Sons. Reproduced from Amboni M, Barone P, Hausdorff JM. Cognitive contributions to gait and falls: evidence and implications. *Mov Disord*. 2013;28(11):1520–1533.[31]

Verghese et al,[33] involving sedentary seniors who played "computer games", showed an improvement in usual walking and dual-tasking gait speed, and this clearly illustrates the potential of cognitive therapy.

Cognition plays a dominant role in gait preservation while pathology and/or age dampens the automaticity of gait; however, the interpretation of the interplay between cognition and gait may be influenced by the selection of gait measures, protocols, and the analytic approach.[34] In the following section, some of these issues have been considered.

Different apparatus and paradigms to assess gait

Normal walking

The assessment of gait speed at self-selected pace over 4 meters is the most commonly used, as it is a quick and safe method, being clinically relevant for the evaluation of risk of falls, cognitive impairment, institutionalization, and mortality.[35] A departure from this strategy is acceptable for some gait characteristics but not for all. Gait speed in PD has proven to be reliable, with good test–retest reliability, over 10 meters and 6 minutes for comfortable self-selected gait speed and for fast walking in clinical and home environments.[36,37] However, this is not the case for gait variability, where reliability and clinimetrics improve with increasing number of steps, requiring at least 120 steps.[38,39] Gait is less variable when walking continuously, like on a treadmill, compared with that when performing multiple short intermittent walks.[40] This clearly highlights the importance of the testing protocol, which is how different apparatus and paradigms influence the outcomes. In a study by Galna et al,[38] gait variability was measured twice with an interval of 1 week in 27 older adults and 25 PD patients. The participants walked at their preferred pace during 1) a continuous 2-minute walk and 2) 3 intermittent walks over a 12-m walkway. The gait variability was calculated as the within-person standard deviation for step velocity, length and width, and step, stance and swing duration. The authors found that continuous walking protocols may be more reliable as they measure gait under steady state conditions thus reflecting more automatic gait control unconfounded by the repeated shifts of attention associated with short intermittent walks (Figure 3).

Treadmill

Another important question is whether the evaluation in treadmills is a good protocol to infer the underlying gait pathology. Even more, it is even questionable whether the treadmill assessment appropriately reflects the normal ground walking. Analyzing gait in a treadmill is a considerably more practical system of analyzing gait in a clinical environment but, more importantly, it may form the last resort when normal walking on flat ground is not feasible in advanced stages of neurological diseases. Moreover, in patients with considerable postural instability only being able to walk with external help, a treadmill with a harness may be the only system to adequately measure rehabilitation protocols.[41] Indeed, it has been demonstrated that treadmill training improves gait speed, stride length, without improving cadence or walking distance.[41] The comparison of 2 walking training programs, one performed on a treadmill and another over the ground, showed that only the former led to improvement in the stride length at the preferred and maximal speed in PD.[42] These findings justify the use of treadmill as a potential therapeutic approach in PD patients. However, treadmill limits the assessment of some gait variables, such as gait variability, probably due to the proprioceptive cues and rhythmicity provided by the belts of the treadmill.

Dual-task paradigms

In contrast to single paradigms (eg, walking free at desired running speed) in dual-task paradigms, the patient also
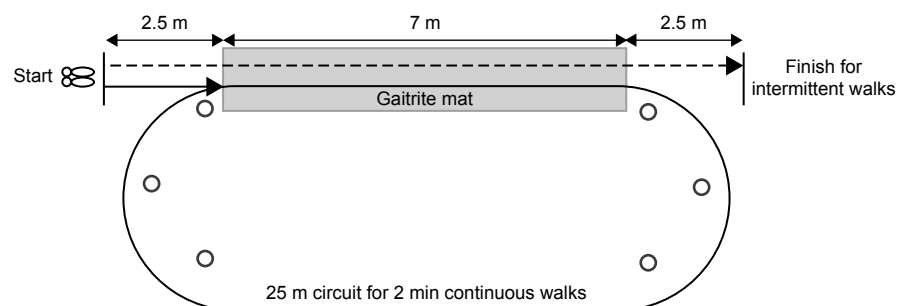

Figure 3 This figure depicts the laboratory setup for testing continuous and intermittent walks.
Notes: The authors highlight that continuous walking protocols may be more reliable. Reprinted from *Gait Posture*, 37(4), Galna B, Lord S, Rochester L, Is gait variability reliable in older adults and Parkinson's disease? Towards an optimal testing protocol, 580–585, Copyright (2013), with permission from Elsevier.[38]

performs a cognitive task (eg, walking and arithmetic) on top of the automatic locomotor and postural control. Dual tasks are mainly cognitive, and they vary widely from a simple "walking while talking" to counting backward in serial order. Some of these cognitive tasks may be concurrent with the same networks that are also involved in postural and locomotor control.[31] This evidence has reinforced the use of dual-tasking paradigms in order to decrease compensatory cognitive control on gait and make latent motor deficits more emerging. Consequently, dual-tasking paradigms also expose the level of compensatory cognitive control required to maintain gait performance. Indeed, walking under cognitive strain; walking while talking, by cognitively stressing locomotion demands, might help in the identification of dysfunction much early, and are therefore a more sensitive measure of the underlying pathology, and a robust predictor of frailty, disability, and mortality in high-functioning older adults.[43] In PD, Stegemoller et al[44] have shown that impaired gait performance under dual-tasking conditions (eg, slower gait speed and increased variability) is intrinsic to PD and correlated to the cognitive processing speed. However, caution is required while using these protocols, because dual-task interference is also a feature of healthy aging. Recent work by Smulders et al,[45] in a large cohort of PD patients, after correcting for baseline group differences, have questioned the advantages of dual-task paradigms for predicting falls due to the wide variation in response between different individuals. Pieruccini-Faria et al[46] examined, under cognitively demanding conditions (with and without an auditory digit monitoring dual task), the role of dopaminergic treatment on gait when approaching an obstacle to be stepped over. They also assessed visual strategies in these conditions, as a reflection of movement planning. They concluded that dopamine influences planning by limiting sensorimotor processing capacity, especially in the presence of increased cognitive demand in PD. More interestingly, the factor that can be interpreted as a burden for gait performance can be potentially used as a tool for rehabilitation. Orit Segev-Jacubovski et al illustrated the potential utility of multiple, diverse forms of cognitive therapy for reducing the risk of falls.[30] To sum up, although dual-task tests have been generally adopted, there is no consensus with respect to its optimal protocol, warranting further refinement in future studies.

Obstacle crossing and negotiation behavior

Balance impairments throughout walking and tripping when negotiating obstacles are the 2 most common causes of falls in older adults.[12] Walking over obstacles implies 4 main tasks: 1) to maintain balance; 2) to prevent tripping during crossing; 3) to prevent slipping during landing; and 4) to progress the body forward. Inaccuracy in movement during obstacle crossing could result in tripping on the obstacle or slipping due to foot strike. In addition, a loss of balance while maneuvering an obstacle may result in sudden and inappropriate movements of the lower limbs that lead the foot to contact the obstacle rather than ignore it. Pan et al[12] have shown, in older adults, that the height of the obstacle increases the strategy of the leading limb changes. Moreover, the subjects with increased risk of falls demonstrated lesser symmetry between the leading and trailing legs and a narrower step width, which are the features that increase the likelihood of tripping. Caetano et al[8] have shown that older adults shorten the previous step before obstacle crossing, reduce the velocity of both previous and obstacle steps and increase the time spent in double support. Also, the reduced step length, adopted by the older adults, correlated with the increased number of steps taken to approach the target.[8]

In PD, there is mounting evidence that gait impairment is amplified during obstacle crossing. PD patients choose a more conservative strategy when crossing an obstacle, with a greater concern for safety margins in relation to the obstacle, leading to greater caution and slower speeds and increased toe clearance.[9] This was proved in a study by Stegemöller et al,[9] where the authors analyzed obstacle-crossing behaviors using a paradigm of 5 trials of normal walking and 5 trials of obstacle crossing. Regarding both tasks, the participants walked barefoot along a 9-m walkway at their normal, comfortable pace. The participants crossed the obstacle located in the middle of the path and continued walking to the end of the walkway. This lightweight obstacle was constructed of a wooden dowel crossbar (91 cm long and 1.27 cm in diameter) and was supported by 2 vertical standards (Figure 4A). Regarding the obstacle clearance parameters, PD patients performed with a greater mean of vertical clearance height in both the leading and trailing feet traveling over the obstacle. In addition, PD patients, due to slower crossing speed, spent a longer time in a single support, positioned their stance foot closer to the object, and the leading foot helped them clear the object with a greater safety margin than their age-matched control subjects (Figure 4B).

Regarding the untouched issue, how the CNS controls postural stability during gait initiation with the goal to clear an obstacle, Yiou et al[47] requested the healthy subjects to initiate gait as fast as possible in 3 different conditions of obstacle
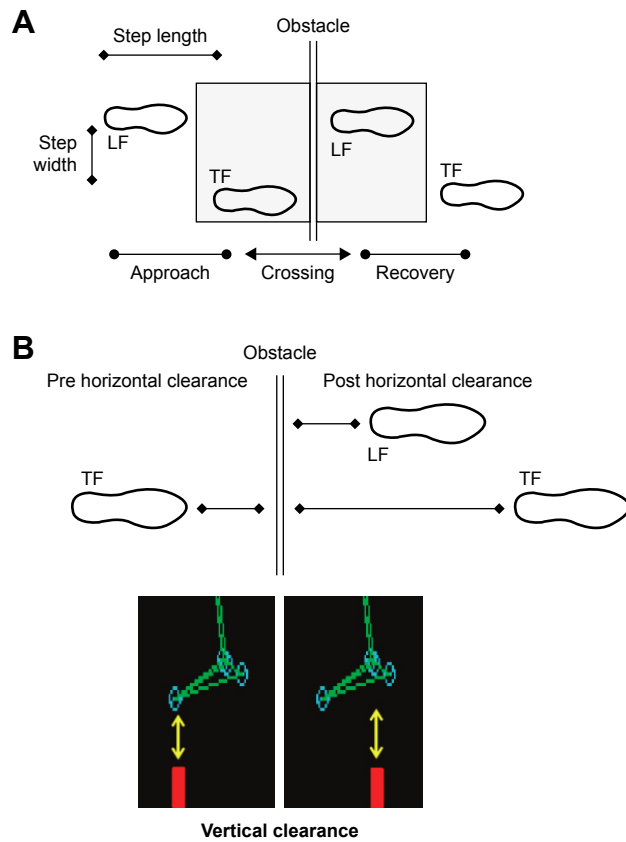
A

Step length

Obstacle

Step width

LF

LF

TF

TF

Approach — Crossing — Recovery

B

Obstacle

Pre horizontal clearance   Post horizontal clearance

LF

TF   TF

Vertical clearance

Figure 4 (**A**) Examples of apparatus and gait parameters used to calculate the approach, crossing, and recovery steps during obstacle crossing. (**B**) An example of horizontal and vertical obstacle clearance parameters.
Note: Reprinted from *Arch Phys Med Rehabil*, 93(4), Stegemöller EL, Buckley TA, Pitsikoulis C, Barthelemy E, Roemmich R, Hass CJ, Postural instability and gait impairment during obstacle crossing in Parkinson's disease, 703–709, Copyright (2012), with permission from Elsevier.[9]
Abbreviations: LF, leading foot; TF, trailing foot.

height, 3 conditions of obstacle distance, and 1 obstacle-free (control) condition. The authors investigated the stabilizing features of gait initiation (Figure 5), analyzing APAs, and lateral swing foot placement. In their work, it was found that the anticipatory peak of backward center-of-pressure shifted and the initial forward center-of-mass set decreased with obstacle height, probably in an order to limit the risk to trip over the obstacle, while the forward center-of-mass velocity at foot-off increased with obstacle distance, allowing a further step to be taken. Accordingly, the authors suggest that the CNS has the ability to predict the potential instability elicited by the obstacle clearance and that it scales the spatiotemporal parameters of APAs accordingly.

In PD, Rogers et al[48] used a sudden drop or elevation of the support surface to assess the contribution of somatosensory information during gait initiation, comparing APAs for lateral weight transfer and propulsion. The authors have shown that PD patients have a longer APA duration, longer time to first step onset, and slower step speed than controls. This article suggests that a feed-forward neural control of gait initiation, regarding limb load and/or foot pressure, can modulate temporal and spatial components of step initiation. In this perspective, the coupling between posture and locomotion should be augmented in PD.[48]

Obstacle crossing behavior adaptability

Interestingly, APAs can be increased to normal levels when a step is initiated in response to an external cue or when on
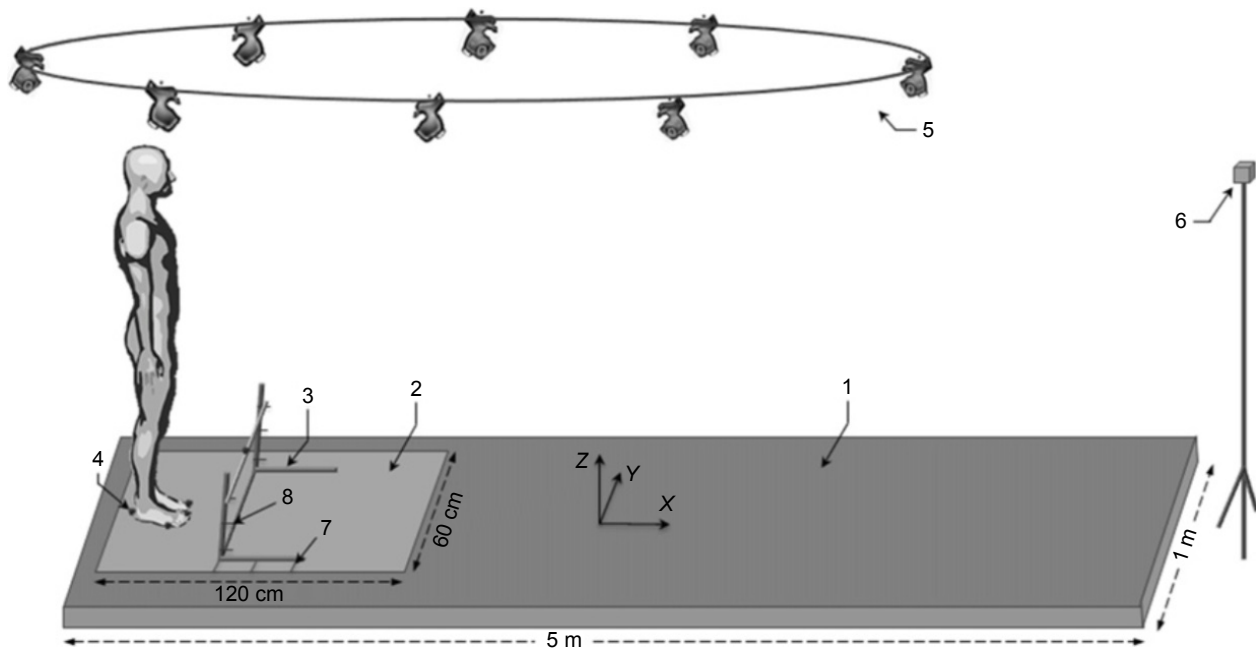

Figure 5 Schematic illustration of the experimental set-up analyzing anticipatory postural adjustments upon gait initiation crossing an obstacle.
Note: Reproduced from Yiou E, Artico R, Teyssedre CA, Labaune O, Fourcade P. Anticipatory postural control of stability during gait initiation over obstacles of different height and distance made under reaction-time and self-initiated instructions. *Front Hum Neurosci.* 2016;10:449.[47]

levodopa.[49] Without levodopa, the step initiation in PD subjects was characterized by decreased production of force, decreased the velocity of movement, and slowed execution of the APAs for self-generated step. These impairments were significantly less evident when the PD subjects were on levodopa therapy. Interestingly, an external stimulus improved and increased the force and the velocity of step initiation in healthy subjects and also in PD patients. In other words, dopaminergic therapy and an external stimulus similarly improved the deficient force production for the APAs associated with step initiation in PD.[49]

There is growing research on neurophysiology supporting rehabilitation interventions, focusing separately on isolated components of posture, balance, and gait in PD.[2] In addition, the rehabilitative interventions to assist lateral displacement of the APA may be beneficial in improving steps in patients with PD. Still, it is important to bear in mind that the coupling between posture and locomotion affects the effectiveness of these rehabilitation strategies, justifying a global approach.[2] The ability to quickly adapt postural responses based on the task and environmental context is altered in PD, involves basal ganglia networks but probably is levodopa-resistant.[50] Chong et al[50] have shown that if the postural perturbation direction is altered unexpectedly, healthy adults immediately adapt their postural responses by changing postural muscle activation patterns; and, in contrast, PD patients take several trials before exhibiting the appropriate postural response to the new perturbations, unresponsive to levodopa medication. As such, the authors concluded that PD patients have more difficulty in using cognitive set to modify their responses, particularly when instructed to "resist" the perturbations. This may represent a relative "inflexibility" to alter postural responses to match changes in task conditions or contexts, or in other words, an impaired learning and adaptability, by trial and error, in PD.[50] Still, in the work by Jacobs et al,[51] it was shown that PD patients could increase their size of stepping responses to external perturbations when these patients could see their legs as they stepped toward a visual target. PD patients exhibited short compensatory steps due to abnormal proprioceptive-motor integration and used visual input to take longer compensatory steps when a target was provided, moderately responsive to levodopa in moderate stage PD patients. Still, in more severely impaired PD patients, neither visual input (viewing the target and in unobstructed vision) nor levodopa provided a significant improvement. These results led the authors to conclude that the degeneration of dopamine circuits within the basal ganglia is not responsible for the proprioceptive-motor deficit that degrades compensatory steps in PD.[51] Interestingly, this innovative

experiment paves alternative rehabilitation strategies using augmented proprioception, especially vision, in PD.

Chang et al[52] determined the effect of Tai Chi Chuan exercises on obstacle-crossing behavior. In the study, 15 healthy older adults practicing Tai Chi Chuan (3 days a week for 5 or more years) (the Tai Chi group [TCG]) were compared with 15 normal healthy older adults who did leisure exercises (walking or jogging) for the same time. Kinematic parameters (by a Vicon motion analysis system) and ground reaction forces (by Kistler force plates) were synchronously recorded (Figure 6). The different crossing strategies between the TCG and the general group were addressed and it was found that the differences between the strategies accounted for the differences in obstacle-crossing performance in older adults. With regular Tai Chi Chuan training, older adults improved their physical capabilities and adopted a more efficient strategy, that is, paying less attention to crossing the obstacle and by increasing the vertical clearance of the leading foot and the vertical clearance of the trailing foot (defined as the minimum distances when the toe markers were vertically above the obstacle) by flexing the hip of the leading leg more, which enabled them to cross the obstacle safely and at a faster speed. The authors concluded that regular Tai Chi Chuan training in older adults may improve their physical capabilities and help in adopting a more efficient strategy.[52]

Table 1 summarizes the findings on the relationship between gait and cognition throughout obstacle crossing with aging, in young and old healthy subjects and in PD. In the aforementioned studies, exercise and/or physiotherapy
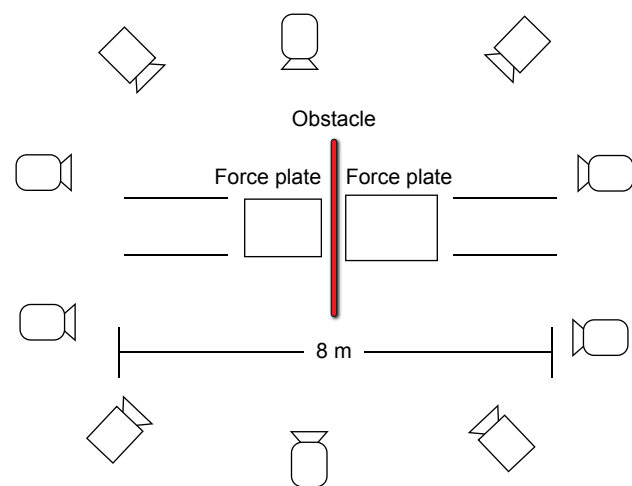

Figure 6 Top view of the laboratory setting of the effect of Tai Chi Chuan training in obstacle crossing behavior, analyzed by kinematics (Vicon motion analysis system) and kinetic ground reaction forces (Kistler force plates).
Note: The effect of Tai Chi Chuan on obstacle crossing strategy in older adults. Chang YT, Huang CF, Chang JH. *Research in Sports Medicine.* 26 Jun 2015. Reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com).[52]

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Table 1 Relation between gait and cognition throughout obstacle crossing in young and old healthy subjects and in Parkinson's Disease

Study	Participants		Protocol	Gait assessment	Temporal and/or distance constraints	Results
	Age	Number				
Young and old healthy subjects						
Pan et al[12]	≥55	Older adults at low (n=10) vs high risk of falling (n=10)	Performed barefoot obstacle crossing along a 6-m walkway at a self-selected speed	The subjects were classified as being at high or low risk of falling by the Tinetti Balance and Gait test (a score of >36 or <36, respectively). Gait kinematics was evaluated in different obstacle heights subsets, at 10%, 20%, and 30% of leg length	Yes	Individuals at a high risk of falling demonstrated less symmetry between the leading and trailing legs and a narrower step width
Caetano et al[8]	74±7/26±4	Older adults (n=50); young adults (n=21)	Randomly presented gait adaptability trials (3 trials of each) of: obstacle avoidance, short stepping target, long stepping target and no target/obstacle	Gait adaptability was accessed by using a symmetry ratio equation, which provides a comparison of the clearance profile for both legs	Yes	Older adults exhibited a more conservative adaptation strategy characterized by slow, short and multiple steps with longer time in double support, and demonstrated poorer stepping accuracy and made more stepping errors (failed to hit the stepping targets/avoid the obstacle)
Dadashi et al[53]	>65	Older adults (n=1,400)	Analysis of anthropometric characteristics with foot clearance kinematic measurements while walking in a 20-m unobstructed/obstructed corridor	Gait variability (range of the temporal, spatial and clearance parameters) under continuous protocols vs obstacle negotiation strategies	Yes	Provided normative dataset of gait parameters and characterized gait patterns associated with increased risk of falling
Yiou et al[47]	23.2±4	Young adults (n=14)	Subjects initiated gait in three conditions of obstacle height, three conditions of obstacle distance, and one obstacle-free (control) condition	Stabilizing features of gait initiation included APAs and lateral swing foot placement	Yes	Medial-lateral APAs are scaled with swing duration in order to maintain an equivalent stability across experimental conditions. The anticipatory peak of MLCOP shift, the initial ML COMvelocity and the duration of the swing phase, of gait initiation, increased with obstacle height, but not with obstacle distance
Chang et al[52]	>65	Tai Chi group (TCG) (n=15) vs healthy older adults (n=15)	Practice of Yang style and Tai Chi Chuan, of 108 postures. The routine was 3 days a week for 5 or more years with 8-m walkway and a height-adjustable obstacle (different heights of the obstacle [10%, 20%, and 30% of the leg length])	Defined 3 step positions as a crossing stride including stride length, stride time and stride velocity in order to determine foot-obstacle clearances and the flexion angle of the hip, knee, and ankle	No	The TCG group performed significantly faster stride velocities, longer stride lengths, and shorter stride times. TCG could also produce significantly larger forward ground reaction forces to propel the body and were able to make a significantly greater flexion angle of the hip of the leading leg compared with the general group

Table 1 (*Continued*)

Study	Participants		Protocol	Gait assessment	Temporal and/or distance constraints	Results
	Age	Number				
Hollman et al[39]	>65	Older adults (n=24)	Subjects walked during the normal and dual task (backward spelling) walking conditions at self-selected speeds and then repeated the tests. Determined the test–retest reliability of 3 gait parameters (pace, rhythm, and variability) during normal and dual task walking	Velocity, cadence, and variability in stride velocity were measured	No	Fewer than 10 to 20 strides may reliably measure velocity and cadence in either normal or dual task walking. Variability in stride velocity requires hundreds of strides, particularly in dual task walking
Nakano et al[55]	25.6±4.6	Healthy young adults (n=12)	Avoidance of a virtual white planar obstacle by lengthening or shortening their steps under free or constrained conditions (normal-walking/walk-through conditions)	The comparison of X-COM shift and placement of lateral foot during the different obstacle conditions	Dual	Temporal constraints affect postural stability in the AP and ML directions during step adjustments. AP and ML stability at swing foot contact is maintained through adjustments of step length and lateral foot placement, respectively
Ida et al[56]	27.3±4.7	Healthy adults (n=10)	Participants stood upright and lifted one leg to avoid colliding with a real obstacle sliding on the floor toward a participant and with its virtual image (delivered by a head-mounted display or a 3D projector)	The acceleration of the foot, the center of pressure, and electrical activity of the leg and trunk muscles were measured during the time intervals typical for early postural adjustments, anticipatory postural adjustments, and compensatory postural adjustments.	Yes	Reduced activity of the leg and trunk muscles when dealing with virtual obstacles as compared with that seen when dealing with real obstacles
Parkinson's disease						
Pieruccini-Faria et al[46]	69.7 (±9.3)/ 69.3 (±8.9)	PD patients (n=20); healthy age-matched control participants (n=19)	Walking and gaze behavior on approaching an obstacle (baseline/dual-task)	Synchronized gaze and gait data split into an early and late phase prior to the obstacle	No	In the off state, the behavior of gaze had no interactions with phase or condition suggesting that the deceleration and increased variability when approaching an obstacle is the result of a greater demand for online sensory feedback that cannot be compensated for with visual strategies. Dopamine influences planning by limiting sensorimotor processing capacity
Liao et al[14]	67.3±7.1; 65.1±6.7; 64.6±8.6	PD patients VRWii (n=12); PD patients TE (n=12); healthy participants (n=12)	Participants received VRWii group or TE group for 45 minutes, followed by 15 minutes of treadmill training in each session for a total of 12 sessions over 6 weeks. Obstacle crossing required the participants to walk on a 10 m walkway with an obstacle positioned in the middle of the walkway (height of the obstacle was 20% of the subject's leg length)	Three obstacle-crossing variables (stride length and velocity; Vertical toe–obstacle clearance)	Yes	The VRWii group showed a greater improvement in obstacle crossing velocity and crossing stride length

Study	Age	Sample	Method	Measures		Findings
Caetano et al[13]	66±6	IPD patients (n=46)	Randomized controlled trial comparing home-based step training with control (no-intervention). Intervention group participants played a step game 3 times a week for 15 minutes each session for 12 weeks	Gait adaptability performance was assessed at baseline and 12-week follow-up, and accessed with randomly presented gait adaptability trials: obstacle avoidance, short stepping target, long stepping target and no target/obstacle (three trials of each)	No	Home-based interactive videogame step training improves an ability to adapt gait in response to unpredictable stepping targets in people with PD
Pestana et al[18]	NA	PD patients (n=13); healthy subjects (n=13)	Performed 5 trials of unobstructed gait and 10 trials of obstacle crossing (5 crossing trials with each leg) (obstacle height of 15 cm) with and without auditory cues. Auditory cue (controlled by a metronome) was personalized for each individual according to the cadence determined by the 3 trials performed previously to start the experiment	Symmetric index of gait parameters was analyzed in the least and in the most affected limb in the different paradigms	n.i	Auditory cues in unobstructed walking decreased step velocity asymmetry in PD patients but lacked effect during obstacle crossing
Stegemöller et al[9]	62.2±9.1/62.0±9.3	IPD patients (n=10); healthy subjects (n=10)	9 m continuous barefoot walking with 5 trials like 1 step recovery, 1 step approach throughout obstacle crossing and normal walking	Gait parameters, obstacle clearance parameters, and COM motion	Yes	PD is more conservative and more time-consuming in dynamical stability strategy during obstacle crossing; obstacle crossing increased the mediolateral range of motion, margin of stability, duration of single limb support and reduction of the distance between COM and COP
Galna et al[10]		IPD patients (n=20); healthy subjects (n=10)	10 steps at their preferred speed along a walkway and stepped over an obstacle (height 10% of leg length ×600×10 mm)	Spatiotemporal variables were measured using an eight-camera Vicon motion analysis System	Yes	PD approached and stepped over the obstacle slower and with smaller steps, but had a similar foot clearance. Those with PD were also more likely to step on the obstacle because they did not place their foot close enough to the front of the obstacle before crossing it to accommodate for their reduced step length. During the lead limb crossing step, people with PD increased their step width, whereas controls maintained a narrow step width
Smulders et al[45]	64.6±8.1; 66.3±7.5	Non-recurrent PD fallers (n=171); recurrent PD fallers (n=91).	Patients walked 2 times along a 10-m trajectory, both under single-task and DT conditions (combined with an auditory Stroop task)	Dual-task costs were calculated for gait speed, stride length, stride time, stride time variability, step and stride regularity, step symmetry and Stroop composite scores (accuracy/reaction time)	Yes	Stride time, stride time variability, step and stride regularity, and step symmetry did not change under DT conditions. Recurrent fallers did not show different dual-task costs compared to non-recurrent fallers
Galna et al[38]	68.1±7.3/72.2±6.3	PD patients (n=25); Healthy subjects (n=27)	Estimated the reliability of gait variability during continuous and intermittent walking then determined optimal number of steps for acceptable levels of reliability of gait variability	Gait variability was calculated for step velocity, length and width, and step, stance and swing duration	Yes	Gait variability was more reliable in continuous walking protocols with no fewer than 30 steps

(Continued)

Table I (*Continued*)

Study	Participants		Protocol	Gait assessment	Temporal and/or distance constraints	Results
	Age	Number				
Rogers et al[48]	72.9±9.3/73.3±9.1	PD patients (n=8); Healthy subjects (n=8)	Perturbation trials, the stance limb ground support surface was either moved vertically downward (DROP) or upward (ELEVATE) trials by 1.5 cm shortly after the onset of the APA phase	APAs for lateral weight transfer and propulsion	No	During ELEVATE trials that opposed the intended weight transfer forces, both groups rapidly adapted their stepping to preserve standing stability by decreasing step length and duration and increasing step height and foot placement laterally. PD patients demonstrated a longer APA duration, longer time to first step onset, and slower step speed than controls
Burleigh-Jacobs et al[49]	66.7±6.2/66.3±6.4	PD patients (n=6); Healthy subjects (n=6)	Healthy subjects and PD patients (ON/OFF levodopa conditions) were instructed to take a forward step with left foot and follow with the right in three conditions: (a) self-generated; (b) perceived a brief, 4-ms current pulse cutaneous cue delivered to the hand or the earlobe; (c) the onset of the cutaneous cue was simultaneous with the onset of a backward surface translation	Ground reaction forces and body kinematics were recorded for self-generated and cutaneous cue-triggered step initiation. The effects of assisting anticipatory postural sway with a surface translation coupled with a cutaneous cue were also examined	No	Levodopa (ON) was able to slightly counteract the decreased force production, decreased the velocity of movement, and slowed execution of the APAs for self-generated step in PD when OFF. Cutaneous cue was beneficial in all groups. The surface translation, both groups executed the APAs for step more rapidly, but the PD subjects, both ON and OFF, failed to increase the force to execute push-off more rapidly
Chong et al[50]	68±9; 26±9; 67±9	PD patients (n=10); 10 healthy young subjects (n=10); healthy older adults (n=10)	The subjects were analyzed in 2 experiments: (1) when the direction of a surface perturbation changed from a backward translation to a toes up rotation; and (2) when subjects were instructed to 'give' or 'resist' while responding to the translations and rotations	The ability to change set was inferred by measuring the change in the amplitude of automatic gastrocnemius or tibialis anterior muscle responses	No	PD patients did not change sensorimotor set (suppression of gastrocnemius responses to toes up rotations) immediately to the first rotation but needed several rotations to change their responses. PD patients had more difficulty in using cognitive set to modify their responses, especially when instructed to 'resist' the perturbations
Jacobs and Horak[51]	62 (49–78); 70 (66–78); 66 (52–78)	Moderate PD (n=5); severe PD patients (n=5); Healthy subjects (n=10)	Compensatory steps in response to backward surface translations in five conditions: with eyes open, with eyes closed, to a remembered visual target, to a target without seeing their legs (wearing a lightweight vest that blocked their view of their legs), and to a target while seeing their legs	Reflective markers positioned in several points of the body, with the 3-dimensional spatial coordinate information about the displacement of body segments calculated by high-resolution video cameras	No	PD patients exhibited shorter compensatory steps. Severe PD patients made larger accuracy errors when stepping toward targets, which was worsened when unable to see their legs. Patients exhibited short compensatory steps due to abnormal proprioceptive-motor integration and used visual input to take longer compensatory steps, unhelpful in more severe cases and unresponsive to levodopa

Abbreviations: AP, anterior-posterior; APA, anticipatory postural adjustments; COM, center of mass; COP, center of pressure; DT, dual-task; IPD, Idiopathic Parkinson's Disease; ML, mediolateral; n.i, no information was available to discern about the use of temporal and/or distance constraints; PD, Parkinson Disease; TCG, Tai Chi group; TE, traditional exercise; VRWii, virtual reality–based Wii Fit exercise; X-COM, extrapolated Center of Mass.

modulated and improved obstacle-crossing behavior and efficiency, not only in healthy older subjects but also in PD patients. It could, however, still be argued if these benefits are only due to an overall better muscular fitness or is a result of a combination of muscular and cognitive benefits, with the latter being consequent to the adaptability and relearning of crossing obstacle behaviors.

Conclusions and future directions

Despite the abundant literature on obstacle crossing in humans, the question of how the CNS controls postural stability and locomotion during obstacle crossing, remains unclear, even more in PD. The effect of aging on the ability to safely negotiate obstacles is paramount since difficulty in negotiating obstacles is one of the key determinants that lead older adults to refrain from walking. With regard to PD, there is paramount evidence that PD patients present an increased risk of falls, such as during obstacle crossing. This increased risk of falling while obstacle crossing is not only due to impairment in postural control and locomotion but also because of an impairment in the gait adaptability and error trial relearning that involves cognitive behavior in PD. In this review article, the authors have put forward the current knowledge on the gait analysis, in particular, the clinimetric properties of obstacle-crossing behaviors during aging and in PD. Dadashi et al[53] made a substantial work, on a large cohort of 1,400 healthy participants, establishing normative values for foot clearance and gait speed parameters. This is a crucial work in order to understand the complex relationship between gait and falls as well as obstacle-negotiation strategies, paving the way for future studies with different apparatus and paradigms. However, in contrast to spatiotemporal parameters (such as gait speed), the variability of gait may better reflect the dynamics of gait, bringing some order to chaos.[21] In addition, when designing apparatus in laboratory–hospital environments, especially when seeking to analyze variability, hundreds of strides, particularly in dual-task conditions, should be collected for reliable data.[39] In spite of all this, when setting apart from laboratory to ambulatory evaluation in future studies, this limitation will be over-ridden and other challenges, such as management of bigger data, will certainly arise.

The interplay between cognition and gait,[30] and the influence of postural instability in PD in reducing the automaticity of gait putting a higher burden on cognitive compensatory strategies have also been discussed. This assertion has been put forward by taking advantage of the dual-task paradigms during gait analysis. However, thinking about the complexity

of daily life environments, the results extracted in laboratory settings may be influenced by the fixed protocols, sometimes poorly ecological, and the analytic approach itself.[34] Neurological diseases impair the structure and function of locomotor and postural control networks, and pathological and/or compensatory changes are reflected in slowness, increased variability, worst postural control and increased risk of falling. This is particularly evident in PD where postural instability is a critical landmark in the progression of the disease. In the present review, the authors have presented several arguments for considering obstacle crossing as a complex task, where several networks, postural control (eg, APAs), gait and cognition (eg, executive functions), visual perception (eg, environment constrictions; obstacle height) and multisensory integration (eg, proprioception), have all converged in order to avoid tripping and falling. In this context, gait analysis protocols taking the use of crossing obstacle paradigms can provide a quick screening tool to identify patients at a risk of falling and evaluate outcomes of training rehabilitation programs. In fact, several promising physiotherapy interventions have already shown robust scientific evidence,[54] contemplating itself as a field of growing interest and investigation. The sensory information, regarding limb load and/or foot pressure, can modulate temporal and spatial components of step initiation and obstacle crossing, and in this perspective, augmenting the interplay between postural control and locomotion (eg, APAs) should be envisioned in future rehabilitation protocols.[48]

Once some of the aforementioned doubts are over-ridden, a better understanding of the impairments of obstacle crossing with aging and in neurological diseases such as PD will be achieved. This will further pave a way to envision the rehabilitation strategies focusing on the repetition and potentiating the learning effect. In addition to muscle strengthening, there is paramount evidence that by trial and error, the behavior of obstacle crossing can be revived and relearned in order to achieve a new and better outcome. Despite potentially slow rates of adaptation and learning in PD, the so-called postural inflexibility of PD,[50] patients can eventually relearn and adapt gait and crossing behavior with repetition. Further, the more breathtaking fact is the expectation that there is a carrying-over effect from cognitive to physical gait domains, thus providing a dual beneficial effect, in cognition, reducing dual-task costs, and risk of falling when crossing an obstacle.[33]

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Disclosure

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