Virtual Reality for Gait Training: Can It Induce Motor Learning to Enhance Complex Walking and Reduce Fall Risk in Patients With Parkinson's Disease?

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Background. Gait and cognitive disturbances are common in Parkinson's disease (PD). These deficits exacerbate fall risk and difficulties with mobility, especially during complex or dual-task walking. Traditional gait training generally fails to fully address these complex gait activities. Virtual reality (VR) incorporates principles of motor learning while delivering engaging and challenging training in complex environments. We hypothesized that VR may be applied to address the multifaceted deficits associated with fall risk in PD.

Methods. Twenty patients received 18 sessions (3 per week) of progressive intensive treadmill training with virtual obstacles (TT + VR). Outcome measures included gait under usual-walking and dual-task conditions and while negotiating physical obstacles. Cognitive function and functional performance were also assessed.

Results. Patients were 67.1 ± 6.5 years and had a mean disease duration of 9.8 ± 5.6 years. Posttraining, gait speed significantly improved during usual walking, during dual task, and while negotiating overground obstacles. Dual-task gait variability decreased (ie, improved) and Trail Making Test times (parts A and B) improved. Gains in functional performance measures and retention effects, 1 month later, were also observed.

Conclusions. To our knowledge, this is the first time that TT + VR has been used for gait training in PD. The results indicate that TT + VR is viable in PD and may significantly improve physical performance, gait during complex challenging conditions, and even certain aspects of cognitive function. These findings have important implications for understanding motor learning in the presence of PD and for treating fall risk in PD, aging, and others who share a heightened risk of falls.

Key Words: Virtual reality—Gait variability—Fall risk—Parkinson's disease—Motor learning.

PARKINSON'S disease (PD) impairs gait and motor function while also impacting cognition, most notably executive function (EF) and attention (1,2). These deficits further exacerbate difficulties with mobility, especially during complex and "dual-task" (DT) gait activities when patients are required to walk while performing another task. As in the general elderly population (3–8), in PD, EF, attention, and DT abilities have been associated with fall risk (9–11).

Traditional treatment approaches in PD have focused mainly on symptom relief to maximize function and minimize secondary complications. Indeed, until recently, the assumption has been that motor learning cannot take place in the presence of impaired basal ganglia (12,13). Evidence

from animal models and patient studies suggests, however, that this may not be the case (14–17). Pathways involving the basal ganglia in PD may be capable of plasticity, and their activity patterns may be partly corrected with appropriate intensive training (18–20). To date, improvements in usual walking were reported following treadmill training (TT), while the effects of training on obstacle negotiation, complex walking, and DT abilities are still largely unexplored (21). In addition, it is not clear if training in patients with PD can transfer beyond the task that was specifically trained or if long-term retention is possible (17,22).

To address these questions, we employed virtual reality (VR), a relatively new intervention modality in the field of neurorehabilitation. VR applications can provide visual,

auditory, and haptic inputs. Theoretically, this multisensory feedback enhances motor learning through problem solving, while promoting the performance of multiple repetitions of movement. VR-based training in the poststroke population has shown encouraging results for improving gait speed, endurance, and force production and for treating cognitive deficits, such as EF (23,24). To date, however, only one case study has been published on the use of VR for gait training in PD (25).

The objectives of the present study were to demonstrate the possibility of using TT + VR in patients with PD and to examine the effectiveness of TT + VR for improving gait, DT abilities, and obstacle negotiation, known mediators of fall risk. We evaluated the effects of training with TT + VR immediately after the cessation of the training period and 1 month postintervention to explore the possibility of retention. Finally, to begin to assess and isolate the added value of TT + VR, in contrast to TT alone, we compared the results of the present study with those from a previous investigation of TT, without VR, in patients with PD.

METHODS

Participants

Twenty patients with idiopathic PD participated in this study. Patients were all moderately impaired (Hoehn and Yahr Stage II–III), taking antiparkinsonian medications, and had walking difficulties (defined by the Unified Parkinson's Disease Rating Scale [UPDRS] motor part) but were able to walk unassisted for at least 5 minutes. Exclusion criteria included coexisting serious chronic medical illnesses (eg, orthopedic, psychiatric, or neurological), severe visual deficits, major depression, or dementia. All participants provided informed written consent as approved by the local human studies committee.

Procedures

A repeated measures design (pretraining, posttraining, and follow-up at 4 weeks) was used. The study was an open-label trial; however, a comparison was made to a historical active control group of patients with PD who followed a similar protocol of TT but without VR. All testing occurred in the "on" state (approximately 1 hour after medication intake).

Patients were asked to walk in a well-lit corridor under three conditions each of 1 minute: (i) walk at comfortable speed, (ii) walking while serial 3 subtractions from a predefined number (DT), (iii) walking while negotiating two obstacles (box: 50 cm W × 30 cm D × 40 cm H and lines: 50 cm W × 40 cm D apart) placed on the floor at specific locations. The 6-minute walk test assessed endurance measured as the total distance walked in 6 minutes (26).

The GaitRite mat, a sensorized 7 m carpet (CIR Systems, Inc., Haverton MA), quantified spatial features of gait, such

as stride length. Overground obstacle negotiation was evaluated by step length and effective obstacle clearance. The physical obstacles (see earlier) were placed on the GaitRite. The distance between the heel and the physical obstacle during the loading response of the lead foot was measured to assess clearance and efficient obstacle negotiation.

A small lightweight accelerometer (Mcroberts, The Hague, The Netherlands) was worn on the lower back of the patients during all gait measurements to quantify temporal measures, such as stride time and gait variability. Gait variability (ie, the inconsistency from one stride to the next) was determined by calculating the magnitude of stride-to-stride fluctuations, normalized to each participant's mean stride time, using the coefficient of variation (CV = 100 × standard deviation/mean) (27). Spectral analysis of the calibrated acceleration signal was applied to the locomotion band (0.5–3.0 Hz). The width of the main (dominant) frequency in the anterior–posterior axis was extracted; a narrower peak reflects lower gait variability and reduced stride-to-stride fluctuations.

The UPDRS motor part (part III) (28) quantified disease-related motor symptoms and the Four Square Step Test assessed overground obstacle negotiation, dynamic balance, and fall risk (29). The Parkinson's disease quality of life questionnaire (PDQ-39) (30) assessed quality of life. The Montreal Cognitive Assessment (31) characterized baseline cognitive function, and the Trail Making Test (TMT; color version) was used to assess the effects of the intervention on cognitive function. The TMT A evaluates scanning ability and upper extremity motor function, and TMT B evaluates set shifting, an aspect of EF that has been previously related to mediators of fall risk and future falls (3,4). Performance on the DT activities was evaluated based on the number of subtractions made, the number of errors made, and the DT cost, a measure that reflects the effect of the second task on gait ability, as compared with baseline walking, that is, DT cost = 100 × (single-task gait speed − DT gait speed)/single-task gait speed.

Intervention

The VR simulation was designed specifically for this study. It required the participants to process multiple stimuli simultaneously and challenged them to make decisions about obstacle negotiation in two planes, while continuing to walk on the treadmill. These decisions were made more difficult with distracters, such as changes in lighting and moving objects in the simulation and by adjustment of the frequency and size of the virtual obstacles. Thus, the virtual environment imposed a cognitive load that demanded attention, response selection, and the processing of rich visual stimuli involving several perceptual processes (see Figure 1).

The intervention lasted 6 weeks (three sessions per week). Training progression was based on an earlier study protocol of intensive progressive individualized TT without VR in
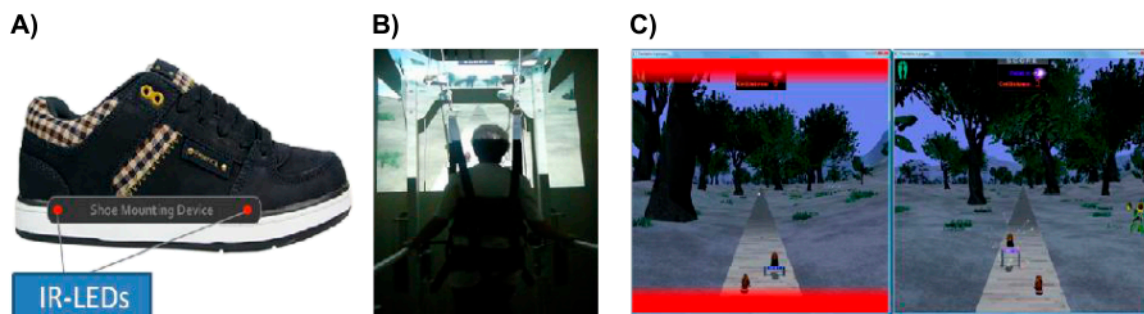
Figure 1. The virtual reality system developed for this study. (**A**) Two light-emitting diodes (LED) were attached to the lateral side of each participant's usual shoes to track movement of the feet. (**B**) A participant walking on the treadmill with a safety harness (without body weight support) while viewing the virtual environment. (**C**) The outdoor virtual environment. Sample feedback can be seen (eg, red bars: negative feedback and lights in the picture: positive feedback).

patients with PD (with similar disease duration and UPDRS scores) (18). In both studies, participants walked on the treadmill with a safety harness that prevented falls but did not provide body weight support. Briefly, overground gait speed over a 10-m walkway was measured at the beginning of each week. During Weeks 4–6, the target was 10% greater than overground gait speed. Each training session lasted about 45 minutes and started with 5 minutes of "warm up" (only walking on the treadmill). After each warm-up phase, the VR simulation was introduced. The speed, orientation, size, frequency of appearance, and shape of the targets were manipulated according to individual needs following a standardized protocol designed to achieve a success rate of 80% in clearing the obstacles to promote engagement and motor learning. Thus, for example, if a patient was able to clear all obstacles in a trial, the difficulty level was increased. The duration of continuous walking before rest breaks (typically three to five per session initially) and the total walking time were also increased throughout the sessions. Feedback was given to the participant in multiple ways including the scoring on the obstacle avoidance tasks and auditory and visual feedback if the subject contacted a (virtual) obstacle.

Statistical Analysis

All clinical and gait variables were examined for normality, and means and standard deviations were calculated. Analysis of differences across time was performed using repeated measures (time) analysis of variance with a Bonferroni correction for multiple comparisons. Post hoc comparisons were used to investigate differences between time periods and conditions (Bonferroni correction: 0.005). Statistical analyses were performed using SPSS (version 16). A significance level of .05 was set for all analyses.

RESULTS

Participant characteristics are presented in Table 1. All participants completed the training with no adverse events. The average net training time in the initial session was 20.0 ± 1.1 minutes; total training time increased to 42.3 ± 1.7 minutes in

the last session. During the initial session, patients had a mean of 17% errors in negotiating the virtual obstacles (as a percent of the total obstacles in the session). In the last session, the mean error percent decreased to 9%.

Gait Measures

Gait speed during usual walking increased by 8.9% after training ($p = .006$). Stride length and stride time also improved (Table 2). Training effects on gait speed, stride time, and stride length were maintained at follow-up. Gait variability during usual walking was not different after training ($p = .43$).

Gait during dual tasking.—DT gait speed improved by 17.4% ($p = .032$), with significant improvements in stride length and stride time ($p = .016$ and $p = .046$, respectively; see Table 2). DT gait variability also improved significantly after training, decreasing from $2.26\% \pm 0.83\%$ to $2.07\% \pm 0.79\%$ ($p = .04$); and further improvements were observed at follow-up ($1.64\% \pm 0.55\%$; $p = .029$). Spectral analysis results were consistent with these findings. The width of the dominant frequency was smaller (ie, sharper, reflecting a less variable gait) after training (from 0.18 ± 0.06 to 0.14 ± 0.03 Hz; $p = .03$), and this effect was maintained at follow-up (0.13 ± 0.01 Hz; $p = .05$).

The gains in gait speed and stride length during usual walking were similar to those observed in a previous 6-week intervention study in patients with PD, except that it

Table 1. Participants Characteristics (*N* = 20)

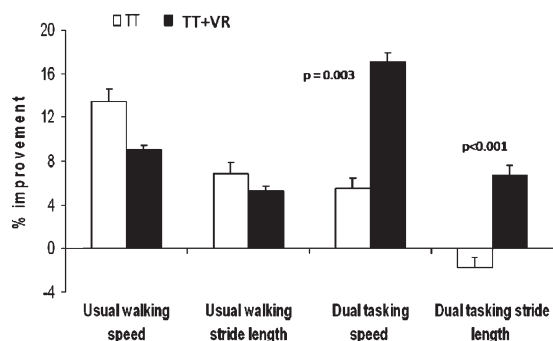|	*M ± SD*	Range
Age (y)	67.1 ± 6.5	55–79
Gender (M/F)	14/6	—
Disease duration (y)	9.8 ± 5.6	4–24
Education (y)	14 ± 2.6	11–21
Hoehn and Yahr staging	2.2 ± 0.4	2–3
Unified Parkinson's Disease Rating Scale part III (motor)	26.5 ± 7.6	14–43
Montreal Cognitive Assessment	25.7 ± 1.7	22–29
Geriatric Depression Scale	3.39 ± 2.6	0–10

Figure 2. Effects of the TT+VR intervention on overground gait speed and stride length. Percent improvement after training with TT + virtual reality compared with TT alone (18). Dual tasking performance improvements were greater after TT + VR compared with TT alone.

included only TT (without VR) (18). However, gains in performance under the DT condition in both gait speed and stride length were significantly larger after training with TT + VR as compared with treadmill alone, with a lower negative DT effect on gait (Figure 2).

Gait during endurance testing.—Endurance, as measured by the distance walked during 6 minutes, improved after training (p = .004) by a mean of 17% in distance walked, amounting to an increase of 59 m. This improvement was maintained at follow-up (recall Table 2). Gait speed during the 6-minute walk test improved by 16% after training (p = .004), with retention at follow-up (Table 2).

Obstacle negotiation.—Gait speed during overground walking while negotiating obstacles improved after training, and this gain was maintained at follow-up (Table 2). Immediate and retention effects of training were also observed in step length during overground obstacle negotiation. Foot placement (initial contact) after crossing

over the obstacle improved further. Patients took a larger step when crossing over the obstacle, increasing the distance between the foot and the obstacle by 52% (p = .04; Figure 3).

Effects on Cognitive Function and Other PD Symptoms

Patients made 31% less mistakes on the cognitive task after training compared with pretraining values on the serial subtraction task. In addition, the DT cost, as calculated during gait, decreased (improved) by 56% (p = .027) after training (Table 3). Improvements were also observed in the time to complete the TMT in both parts A (p = .003) and B (p = .05; Table 3). Furthermore, after training, a significant association was found between the change in the TMT (TMT B − A), a measure representing EF, and gait speed during DT (r = −.749, p = .013) and obstacle negotiation conditions (r = −0.815, p = .002). Significant improvements on the UPDRS motor scores, the Four Square Step Test, and the PDQ-39 were also seen posttraining, with many effects persisting at follow-up (Table 3).

DISCUSSION

To our knowledge, this study is the first to examine the effects of TT with VR on the mobility of patients with PD. The results indicate that intensive and progressive TT with VR is viable for patients with PD and may significantly improve physical performance and gait beyond the previously reported improvements of TT alone. Complex gait conditions such as walking with a DT, obstacle negotiation, and even certain aspects of cognitive function appear to be positively affected by this intervention.

After 6 weeks of intensive TT + VR, the participants exhibited a change of three points on the motor UPDRS, a clinically significant improvement (32). A mean improvement of seven points in the mobility domain (data not

Table 2. Training Effects on Gait Measures

Test Condition	Pretraining	Posttraining	Follow-Up	*p* Value
Usual gait				
Speed (m/s)	1.16 ± 0.18	1.26 ± 0.20*	1.28 ± 0.19†	.006
Stride time (s)	1.08 ± 0.07	1.04 ± 0.05*	1.04 ± 0.09	.021
Stride length (cm)	123.08 ± 17.22	129.78 ± 18.20*	133.18 ± 15.65†	.043
Dual-task gait				
Speed (m/s)	1.01 ± 0.23	1.17 ± 0.15*	1.13 ± 0.17	.032
Stride time (s)	1.15 ± 0.11	1.10 ± 0.07*	1.08 ± 0.09†	.016
Stride length (cm)	113.07± 23.70	121.31 ± 24.21	126.32 ± 15.88†	.046
Gait during endurance testing				
Speed (m/s)	1.01 ± 0.18	1.16 ± 0.18*	1.13 ± 0.16†	.004
Stride time (s)	1.13 ± 0.24	1.04 ± 0.07*	1.06 ± 0.13	.246
Obstacle negotiation				
Speed (m/s)	0.96 ± 0.19	1.17 ± 0.22*	1.17 ± 0.20†	.001
Stride time (s)	1.10 ± 0.09	1.05 ± 0.07*	1.06 ± 0.10	.232
Stride length (cm)	147.97 ± 16.97	160.66 ± 17.79*	161.46 ± 17.47†	.019

Notes: *p* Values in the right column are for the overall repeated measures analysis of variance models.
* Significant immediate effects at posttraining.
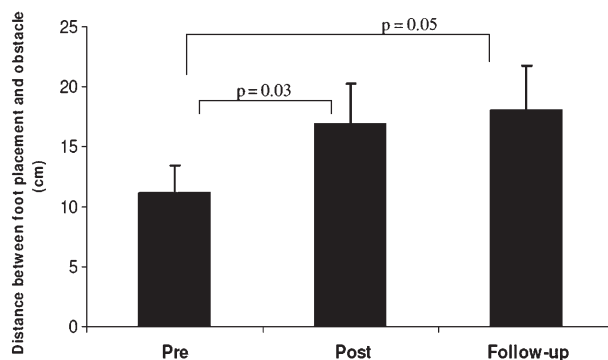† Significant retention effects as compared with baseline evaluation analyzed in post hoc analysis.

Figure 3. Effects of the intervention on obstacle negotiation abilities. The distance between the physical obstacle and foot placement at initial contact after crossing the obstacle became larger (ie, improved) after the intervention.

shown) of the PDQ-39 was also seen, reflecting an effect that is more than four times larger than the minimum clinically significant difference (33). Improvements were also observed in the cognitive domain of the PDQ-39, which focuses on self-reported attention and memory deficits. These findings highlight the beneficial effects of TT + VR on both motor and cognitive symptoms of PD.

The effects of TT + VR on cognitive function were seen in multiple ways. DT costs improved dramatically (31%) after training, reflecting better ability to divide attention. Improvements were also observed in tasks that share properties of the challenging characteristics of the virtual obstacle navigation but were not specifically trained, for example, the Four Square Step Test and TMT. The improvements in section A of the TMT may be a result of the exposure to the complex environment of the VR and the need to scan this environment during training. Improvement in the TMT B likely reflects enhanced EF, set shifting, and planning (2,3,8,34), features that are fundamental to the training. The task demands within the VR may have improved these abilities, which then transferred to complementary tasks.

Training with the TT + VR system also improved gait speed and stride length during the overground obstacle negotiation condition. During obstacle crossing, patients with PD generally place their lead foot closer to the obstacle and more often hit the obstacle as compared with age-matched controls (35). After training with the TT + VR, the distance from the foot to the obstacle increased, consistent with better planning and a safer and more efficient strategy for negotiating obstacles. Indeed, in a study among patients with traumatic brain injuries, scores on the TMT B and obstacle clearance were strongly associated (36), suggesting that poor obstacle clearance is a result of poor planning abilities. After the TT + VR training, we observed significant improvements in both obstacle clearance and scores on the TMT B and a significant association between TMT and gait performance during DT and during obstacle negotiation. The present findings suggest that training with TT + VR promoted the development of new motor and cognitive strategies for obstacle navigation, which transferred to over ground "real-world" activities.

A recent Cochrane review examined eight randomized controlled trials of TT for patients with PD and found evidence for immediate training effects on gait speed, stride length, and walking distance on the treadmill as well as during overground walking (21). The improvements in usual-walking abilities found after training with the TT + VR system in the present study were similar to those found after TT alone (21) (recall Figure 2). The added value of VR can be seen during DT performance when compared with the results of an intensive TT program that used an essentially identical protocol except that it did not include VR and training was four times a week (ie, more intense) instead of the three in the present protocol (18). Baseline characteristics of the PD patients in both studies were similar (eg, the baseline UPDRS motor scores of 29.0 ± 9.3 and the mean gait speed of 1.11 ± 0.17 m/s; recall Table 1). Nonetheless, the negative effects of DT on gait became smaller after TT + VR and were significantly better than those observed after intensive TT alone (recall Figure 2). DT during gait

Table 3. Training Effects on Cognitive and Clinical Measures

	Pretraining	Posttraining	Follow-Up	*p* Value
Cognitive				
Number of errors made during serial subtraction	1.5 ± 1.8	1.0 ± 1.2	0.8 ± 1.2	.16
Dual-task cost	13.9 ± 14.8	6.9 ± 8.4*	12.8 ± 7.6	.05
Trail Making Test A (s)	69.0 ± 15.9	57.2 ± 11.9*	—	.003
Trail Making Test B (s)	141.4 ± 34.9	120.4 ± 18.2*	—	.05
Clinical				
UPDRS motor —part III	26.5 ± 7.6	23.5 ± 6.6*	24.7 ± 7.1[†]	.02
Four Square Step Test (s)	13.3 ± 2.5	11.6 ± 1.6*	11.9 ± 1.6[†]	.009
Quality of life (PDQ-39)	27.4 ± 15.9	19.4 ± 13.6*	23.6 ± 14.5	.04

Notes: *p* Values in the right column are for the overall repeated measures analysis of variance models. PDQ = Parkinson's disease quality of life questionnaire; UPDRS = Unified Parkinson's Disease Rating Scale.

*Significant immediate effects at posttraining.

[†]Significant retention effects as compared with baseline evaluation as analyzed in post hoc analysis.

generally causes patients with PD to walk slower, with shorter strides, and much higher DT costs than that seen in healthy controls (37,38). In the present study, during the initial training sessions, participants indeed walked slowly, with relatively reduced treadmill speed, and their ability to negotiate the obstacles was impaired. However, this pattern quickly changed as patients learned to perform under multi modal conditions (with distracters) and divide their attention within the VR. This finding is consistent with the observed learning curve within the training sessions, the improvements in the TMT (as noted earlier), and an ability to adapt to different tasks and sensory information in post stroke patients (39). Interestingly, the improvements in DT walking abilities observed here parallel the results of recent cognitive remediation studies that also demonstrated improvement in gait (40) and balance (41) as a result of cognitive training alone. The authors suggested that increased attentional resources positively impacted on DT ability. In the present study, the serial subtraction DT was not a part of the training program, yet, after training with the TT + VR system, patients walked faster during the DT, with longer strides compared with baseline, suggesting an ability to adapt the learned strategy to different tasks. Although, between-task transfer has been already shown in stroke (23,24), this was not previously reported in patients with PD.

There is inconclusive evidence in the extant literature as to learning and retention effects on gait in PD, even after relatively long-duration interventions (6 weeks) (20,22). After TT + VR, gains were maintained for at least 4 weeks, with some outcome measures even improving from the immediate postintervention to the 1-month follow-up. The cognitive requirements of training with the VR may have created a learning opportunity and further fostered development of new movement strategies that prompted behavioral changes. This idea is supported by the improvements in tasks that were not explicitly trained (recall the effects on the Four Square Step Test; see Table 3). The intensive TT + VR training may have encouraged motor adaptation learning and constant attention to environmental characteristics, a feature of motor learning that depends in part on cerebellar activation (42). Thus, one explanation of the observed results—in both the motor and the cognitive domains—is that the intensive progressive TT + VR enhanced the ability to learn new strategies and at least partially circumvent impaired basal ganglia loops. Compensation via other neural pathways might also have played a role.

As noted above, this study raises a number of interesting questions regarding motor learning, efficacy, and clinical utility. Further investigations are needed to more fully sort out the precise mechanisms of action to identify optimal dosing (eg, perhaps twice weekly is sufficient?) and to evaluate long-term effects. It may be slightly premature, but it is also interesting to speculate about how TT + VR may be used as a clinical tool. Treadmills and bicycles are now regularly used in cardiac rehabilitation centers to advance the recovery of cardiac patients. Perhaps, in time, TT + VR can also be prescribed as a tool in rehabilitation or other outpatient settings for use among certain individuals with an increased risk of falls.

The study has a number of limitations. The sample size was small, and the study design did not include a control group to unambiguously rule out the possibility that some of the gains observed may have been due to the attention that the participants received and a placebo effect. Thus, in a sense, it should be considered as a pilot study, and conclusions should be judged in that light. Nonetheless, the results of this first study of TT + VR in PD are quite promising, and the comparison to a historical control group, where participants received an even more intensive training, suggests that important gains were likely attributable to the VR and not to TT alone or a placebo effect. TT + VR apparently positively impacts fall risk mediators and promotes a more stable walking pattern. Thus, an intervention program based on this approach seems likely to favorably impact DT ability and, perhaps, to reduce fall risk, a debilitating phenomenon related to both cognitive and motor capabilities (3–6,34). Moreover, the present findings contribute to the growing body of evidence that suggests that motor and cognitive improvement may be achievable among older adults (40,41), even in the presence of a neurodegenerative disease like PD. Still, larger scale, randomized controlled studies are needed to firmly establish efficacy and the long-term retention effects of TT with VR on cognitive, motor function, and fall risk in patients with PD and in other groups of older adults who share an increased risk of falls.

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