Short-Term Effects of Posture-Assisted Step Training on Rapid Step Initiation in Parkinson's Disease

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Background and Purpose: Anticipatory postural adjustments (APAs) for lateral weight transfer and stability precede and accompany gait initiation. Individuals with Parkinson's disease (PD) show altered APA characteristics with delays in initiating stepping that may reflect impaired interactions between posture and locomotion. The purpose of this study was to determine the short-term effects of a single session of repetitive robotic assistance training with the APA on rapid step initiation in individuals with PD in the medications "on" state and healthy control individuals. Ground reaction forces and step kinematics were recorded.

Methods: Subjects first performed baseline trials of unassisted self-paced rapid forward stepping. Next, a training acquisition series involved 50 trials with a lateral pull applied to the pelvis by a robotic system to assist with the early phase of the APA during stepping. To assess potential retention effects of training, unassisted stepping trials were evaluated immediately after acquisition trials (immediate retention) and one week later (one-week retention).

Results: Overall, the subjects with PD had a longer APA duration ($P < 0.03$), and longer first step duration ($P < 0.04$) than the healthy control individuals. Compared with baseline, APA duration was shorter ($P < 0.001$) and step onset time became earlier ($P < 0.001$) for acquisition trials but these effects were not retained. Step duration, which became shorter ($P < 0.001$) during the late acquisition trials ($P = 0.002$), demonstrated immediate retention ($P < 0.001$) and one-week retention ($P < 0.001$).

Conclusion: Posture-assisted training, affecting the interaction between posture and locomotion, may have therapeutic potential for improving movement performance in individuals with PD.

Key words: *Parkinson's disease, posture, stepping, therapeutic training*

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INTRODUCTION

Disorders of posture and gait are a major source of functional disability in individuals with Parkinson's disease (PD).[1,2] These problems often respond poorly to treatment with antiparkinsonian medications and to other interventions such as deep brain stimulation surgery.[3–5] Hence, physical therapy interventions for improving postural balance and gait are the current best treatment in the clinical care of individuals with PD.[6,7] However, the underlying mechanistic bases and evidence in support of the effectiveness of such rehabilitation approaches in PD are inconclusive.[8]

In PD, the difficulty with initiating gait, referred to as start hesitation, is linked with akinesia, or a lack of spontaneous movement, and the prolonged time it takes to initiate a movement such as stepping.[9,10] During gait initiation, an anticipatory postural adjustment (APA) phase normally precedes and accompanies the initiation of the stepping phase.[11–16] APAs are a general form of postural accompaniment that stabilizes posture and equilibrium before a voluntary movement that, once initiated, potentially disrupts posture and balance or functions as a component of the goal intended action.[17,18] For forward stepping, these APAs involve a sequence of muscle activations and changes in the ground reaction forces that move the net center of pressure (COP) beneath the feet posteriorly and laterally toward the initial swing limb. This motor sequence produces the forces and moments necessary to propel the body's center of mass (COM) anteriorly as part of the whole body stepping movement, and laterally toward the single stance limb for frontal plane balance control before stepping.[19]

In comparison with healthy subjects, the lateral and anteroposterior ground reaction forces characterizing APAs in PD are often abnormally prolonged in duration and reduced in amplitude with a delay in the timing sequence between the beginning of the APA and step onset.[17,20–23] Although the APA is present most of the time during voluntary stepping, it may often be absent in participants with PD.[10,20] Thus, the normal spatial and temporal sequencing between the APA and stepping components of gait initiation is frequently disrupted in PD.

A long-standing clinical observation indicates that difficulties with initiating locomotion movements may be transiently overcome if the normally automatic APAs are assisted manually by the clinician.[1] This observation has motivated therapeutic weight-shifting activities (eg, lateral weight shift in stepping and forward lean in chair rising) for people with PD during movements such as gait or rising from a chair.[24–28] Although this effect could involve the influence of sensory cueing or serve to focus attention, the external postural assistance could also facilitate the postural weight shift that may need to be completed before the release of the step cycle or upward ascent is initiated by the central nervous system.[17,18] It is conceivable that the neural control of these elements may be influenced by directly manipulating the spatial and temporal interaction between postural and stepping movement components.

In PD, the difficulties with achieving the postural prerequisites for stepping could contribute to gait initiation delays and start hesitation, not only because of biomechanical limitations, but also because of adaptive changes in neural control. With postural assistance, the usually prolonged APA duration and reduced amplitude accompanying step initiation in PD could be, respectively, shortened and increased to allow the earlier release of the step. In support of this hypothesis, a previous study[22] demonstrated that robot assistance with lateral weight transfer during rapid step initiation acutely shortened the APA duration and led to an earlier first step onset time in participants with early-stage PD and healthy controls. Moreover, the speed of the first step execution was also faster in the participants with PD. No improvements were observed when an identically timed tug, which gave relatively little mechanical assistance but provided a sensory stimulus to the same site, was used. This suggested that the improvements in performance were not likely attributable to sensory cueing.

An important consideration that was not addressed in our previous study is the extent to which improvements in step initiation may be acutely sustained and retained in the short-term with more extensive posture-assisted training. As an initial attempt to extend this approach to clinical application, the purpose of this study was to determine the short-term effects of a single session of repetitive robotic assistance training with the APA on rapid step initiation in participants with PD in the medications "on" state and healthy control subjects. We hypothesized that the repetitive application of external postural assistance that shortened the APA duration would induce acute adaptive changes in the timing sequence and speed of step initiation that would persist over an extended period of trial acquisition blocks and that changes in performance would be retained immediately after treatment and at one-week post-training.

METHODS

Subjects

Fourteen community dwelling adults participated in this study; seven participants with PD (four men, three women, mean $\pm$ SD, 70.3 $\pm$ 6 years) and seven healthy control individuals matched for gender and approximate age (four men, three women, mean $\pm$ SD, 65.6 $\pm$ 7.6 years). Participants with PD were recruited from the Movement Disorders Clinic at Northwestern Medical Faculty Foundation. Inclusion criteria included individuals having been diagnosis of idiopathic PD and a modified Hoehn and Yahr stage not greater than 2.5.[29] Exclusion criteria for both groups included a history of significant cardiovascular, pulmonary, musculoskeletal, metabolic, or other neurological disorders, and a score of 24 or less on the Mini-Mental State Examination.[30] All subjects signed an informed consent form approved by the Northwestern University Institutional Review Board before participation.

A physical therapist evaluated participants with PD using the Unified Parkinson's Disease Rating Scale (UPDRS) Motor subsection outcome measure as a means of describing the level of severity of the motor deficits in the participants with PD. These were assessed in the medications "on" state. UPDRS served as a clinical measure of the level of motor impairment and functional limitation. All UPDRS raters received training and instructions provided by an experienced Movement Disorders Neurologist. The reliability of UPDRS scoring for both research assistants and physical therapists was established by viewing and rating performance against UPDRS training videotapes. The group characteristics are summarized in Table 1.

Experimental Protocol and Data Collection

Before trials were recorded, each subject practiced walking at his or her maximum possible speed. Foot tracings were taken on a sheet of dark paper using chalk dust applied to the bottom of the shoes to serve as a guide to help maintain consistency of stepping movements during repeated trials. The tracings of the initial foot position were secured over two force platforms (Advanced Mechanical Technology Inc., Newton, MA), and the stepping pattern tracing was extended in front of the subject along the walkway. During recorded trials subjects placed each foot on a separate force platform that recorded the ground reaction forces at a sampling frequency of 500 Hz for seven seconds. The kinematics of 17 passive markers were recorded using a six-camera infrared motion analysis system (Motus Peak Performance System, Peak Performance Co., Englewood, CO), sampled at 60 Hz. The markers were placed symmetrically on the skin and/or clothing; at the foot, ankle, knee, hip, wrist, elbow, shoulder; and on a headband covering the crown of the head and both ear canals.[31] Only the hip and shoulder markers were placed on the subject's clothes.

To determine the preferred limb to initiate stepping, subjects were asked to begin walking and to indicate with which foot he or she would kick a ball placed in front of them. All subjects selected their right foot. For each trial, the subjects were requested to stand naturally with their weight evenly distributed on both feet. Beginning with the preferred foot (ie, their right foot), subjects took three steps forward as fast as they could at any self-selected time following a verbal ready instruction. Subjects generally initiated the step within two or three seconds after the verbal instruction. They were told that they might feel a pull at any time on a belt placed around their pelvis, but to react naturally and continue to step as fast as possible. Stepping instructions were repeated periodically throughout the blocks of trials. Rest breaks were offered as needed.

Step initiation trials were performed under four task conditions. First, 10 initial baseline trials without lateral postural assistance were performed. Second, 50 acquisition training trials were performed during which subjects were pulled laterally at the pelvis to assist the APAs. Third, 10 immediate retention trials without postural assistance were assessed. Five minutes of sitting rest were offered in the middle of the testing session (after 35 trials) and as needed by the subjects. Finally, 10 trials without postural assistance were collected one week after the training session (one-week retention). Participants were tested at the same time of day relative to taking medications for all tests. There was no change in the participants' medications between visits.

The lateral postural assistance was provided by a motor-driven robot system that delivered controlled motion of the subject's pelvis.[32] As illustrated in Figure 1, the pulling cable, connected in series with a beaded metal chain, was attached at one end to the subject's waist belt and at the other end to a pretension unit that minimized the cable slack. The beaded chain portion of the cable was adjusted to be level with the drive table where it passed through a gate controlled by a solenoid. The solenoid was controlled by the data acquisition computer to set it in either an open state or a closed state. The closed state locked a bead in position within the gate allowing the stepper motor to exert a pull on the subject's belt attachment through the pulling cable. At the end of the pull, the solenoid was released in an open-state position to let the subject step forward freely. A position transducer located on the drive table recorded pulling motion. Movable pulleys mounted on an independent height adjustable vertical post accommodated differences in subjects' height (Fig. 1) and were used to direct the pulling perturbation to the cable-pulley assembly oriented laterally to the subjects on the side of the first single stance limb. The characteristics of the waist-pull assist (6 cm, 49 cm/sec, 900 cm/sec^2) were determined based on our previous study.[22] The lateral translation was triggered externally through computer control during the early phase of the APA when the subjects produced a vertical force increase of 5% greater than the average baseline value recorded for the initial swing leg (ie, right leg) as detected by the vertical loading force from the force platform. Based on a previous study,[22] this value of vertical force variation ensured that the lateral assist occurred after the APA onset and not during the natural lateral sway excursions (Fig. 2). A safety harness was worn by all subjects to prevent injury but did not otherwise restrict movement.

Data Analysis

Customized interactive graphical analysis programs (MatLab 6.0, MathWorks Inc., Natick, MA) were used to compute the temporal and spatial characteristics of the APAs and initial stepping responses. As described in previous reports,[14,16,22] the lateral APA is characterized by an initial displacement of the net COP toward the first step side that propels the body's COM laterally toward the side of the single support limb. At the same time, a posterior shift in the COP propels the body forward in the direction of stepping. An unloading of the step limb and continuous upward and forward displacement of the foot represents the beginning of the step cycle.

Ground reaction forces were recorded to calculate the net mediolateral (ML) COP displacement recorded beneath both feet from which the characteristics of the APA (duration and amplitude) were determined. The APA onset was identified when the COP began ML displacement toward the first step foot (when the first derivative of lateral COP is not 0) (ie, the onset of the lateral weight transfer). The APA duration occurred between APA onset time and the instant when the lateral COP reached maximum displacement toward the single stance side before step liftoff (ie, the end of the lateral weight transfer). The APA amplitude corresponded to the maximum stepping side lateral COP displacement.

The first step characteristics (onset, duration, and length) were derived from the motion of the preferred step limb ankle marker. The step onset time was determined relative to the instant of the initial lateral COP change from

TABLE 1. Subject Characteristics

PD Subjects	Age, yr	Height, cm	Weight, kg	UPDRS Motor[a] "on"	Hoehn and Yahr Stage[b]	Medication
P1	71	172.7	102.3	7	2.0	Pramipexole
P2	66	180.3	90.9	21	2.0	Amantadine
P3	62	162.6	68.2	6	1.5	Pramipexole, Trihexyphenidyl
P4	75	182.9	85.0	5	2.0	Carbidopa/levodopa
P5	77	172.7	78.6	18	2.0	Carbidopa/levodopa
P6	76	160.0	70.0	19	2.5	Carbidopa/levodopa
P7	65	154.9	50.0	26	2.0	Carbidopa/levodopa Entacopone, ropinirole
PD Subjects						
Mean	70.3	169.5	77.9	14.6	2.0	—
SD	6.0	10.5	17.1	8.4	0.3	
Controls						
Mean	65.6	172.7	72.8	NA	NA	NA
SD	7.6	13.7	15.7	—	—	

[a] UPDRS (Unified Parkinson's Disease Rating Scale) Motor Subscale total maximum score 108, 108 being the most severe.
[b] Hoehn and Yahr Scale of 0–5: 1, unilateral disease; 1.5, unilateral disease plus axial involvement; 2, bilateral disease without impairment of balance; 2.5, bilateral disease with impaired postural reflexes but recovery on pull back test; 3, mild to moderate bilateral disease with impaired postural reflexes, physically independent.

baseline, ie, APA onset. The duration was defined from the beginning and end of the step as indicated by the vertical velocity of the ankle marker. Step length was assessed as the displacement of the ankle between step onset and end in the forward direction.

Statistical Analyses

Mean values were determined for all subjects and variables. A mixed-model repeated-measures analysis of variance was used to assess between-group differences (participants with PD and healthy controls) and within-group differences (baseline, acquisition, immediate retention, and one-week retention).[33] The 50 acquisition trials with the lateral assist were divided into five blocks of 10 trials (A1–A5). To assess possible differences in performance between early trials (early acquisition) and late trials (late acquisition), A1 and A5 trial blocks were analyzed. Similarly, earlier and later immediate retention performances were represented by the means of trials 1 to 3 (early immediate retention) and trials 7 to 10 (late immediate retention). In cases of significant analysis of variance main effects or interactions, planned post hoc analyses were performed using paired *t* tests with the level of significance adjusted for multiple comparisons using a Bonferroni correction.[34] For all comparisons, a significance level was set at $P < 0.05$.

RESULTS

APA Characteristics

Across all conditions, the participants with PD had longer APA durations than controls ($P < 0.03$) (Fig. 3A). There was a significant main effect of condition ($P < 0.001$) whereby APA duration was shorter ($P < 0.001$) for both early acquisition ($P < 0.001$) and late acquisition ($P < 0.001$) trials compared with baseline trials indicating that the assist did improve subjects' lateral weight transfer. The duration of the APA did not differ significantly ($P > 0.05$) between baseline and retention conditions. There was no significant group by condition interaction.

Step Characteristics

Although the participants with PD generally tended to initiate the first step relative to APA onset later than healthy control individuals, there was no significant between subject effect for the step onset time ($P = 0.11$) (Fig. 3B). A significant within-subject effect ($P < 0.001$) indicated that, compared with the baseline condition, the mean step onset time occurred 104 (early acquisition) and 98 milliseconds (late acquisition) earlier for the participants with PD, and 84 (early acquisition) and 62 milliseconds (late acquisition)

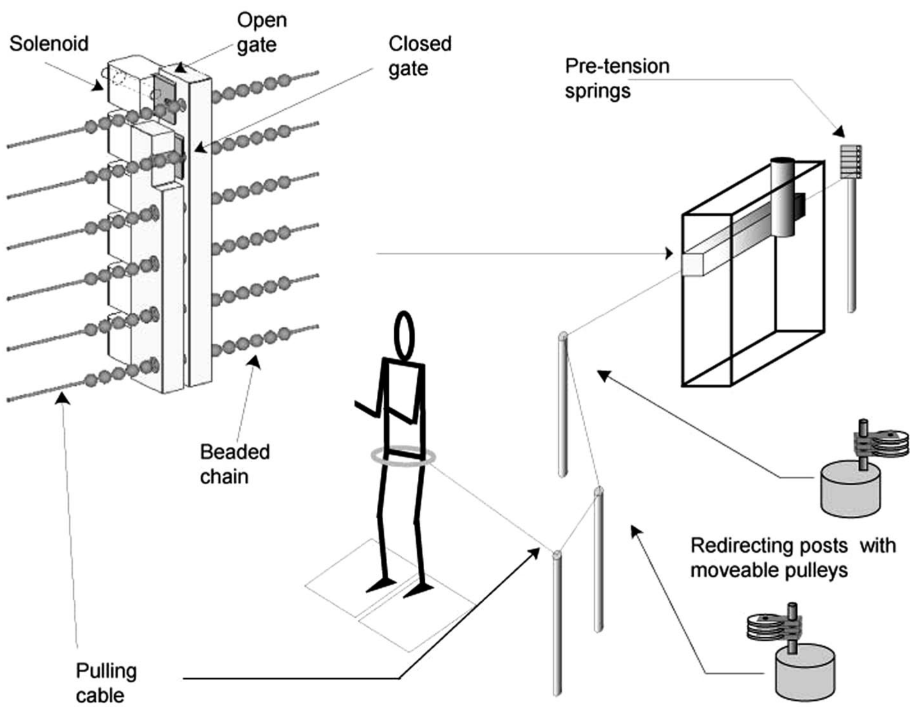

FIGURE 1. Motor-driven robotic waist-pull system. A pulling cable, connected in series with a beaded metal chain, is attached at one end to the subject's waist belt and on the other end to a pretension spring minimizing the cable slack. The beaded chain portion of the cable is adjusted to be level with the drive table, where it passes through a gate controlled by a solenoid. The solenoid was controlled by the data acquisition computer to set it in either an open state or a closed state. For the desired direction of pull (ie, laterally), the closed state locked a bead in position within the gate via the solenoid allowing the stepper motor to exert a pull on the subject's belt attachment through the pulling cable. Movable pulleys mounted on independent height adjustable vertical posts to accommodate differences in subjects' height were used to direct the pulling cable laterally onto the first single-stance limb side.

earlier for the healthy controls ($P < 0.001$). Retention trials were not statistically different from baseline trials.

During step execution, there were no significant between-group effects or within-group effects for first step length (Fig. 3C). However, first step duration (Fig. 3D) was generally longer ($P < 0.04$) across all the conditions for participants with PD compared with controls. Compared with the baseline condition, a significant within-group effect ($P < 0.001$) also indicated that step duration became shorter across the groups especially during the late acquisition trials ($P = 0.002$). Furthermore, this shorter step duration persisted during both immediate retention ($P < 0.001$) and one-week retention ($P < 0.001$) trials.

DISCUSSION

The purpose of this study was to determine the short-term effects of a single session of repetitive robotic assistance training with the APA on rapid step initiation in participants

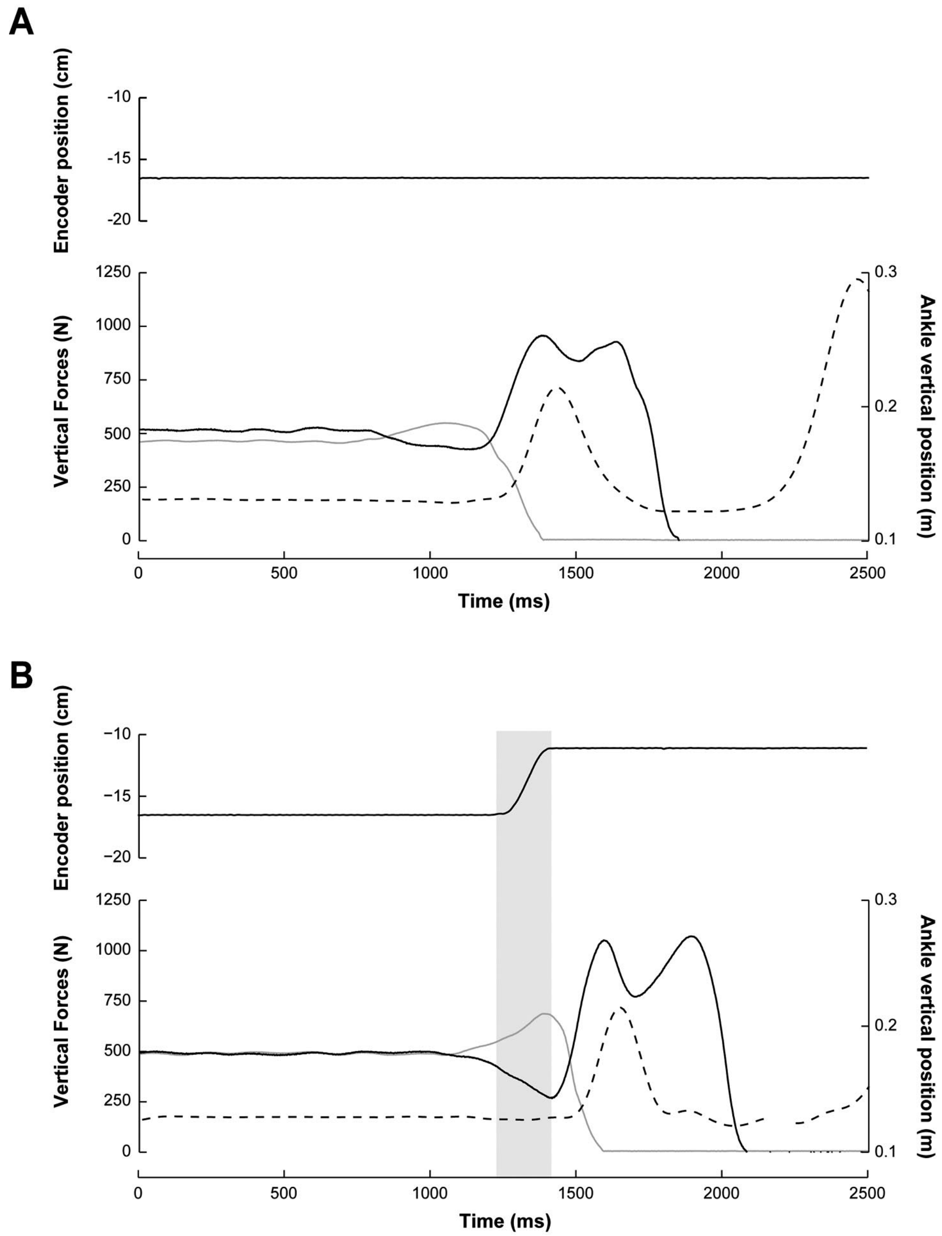

FIGURE 2. A, Representative time histories from a subject with PD showing the vertical ground reaction forces (continuous line) under the initial swing leg (gray) and the stance leg (black), and of the vertical ankle displacement of the swing leg (dashed line) during a typical baseline trial (ie, without postural assistance as observed in the top traces of the motor position encoder). B, Representative time history from the same subject and data types during a typical acquisition trial from the last block of 10 trials (A5) (ie, with postural assistance delivered at the pelvis). The time of the postural assistance derived from the motor position encoder is represented by the vertical gray area.

with PD in the medications "on" condition and healthy control subjects. The results expand on the observations of our previous study[22] and further demonstrated the persistence of the acute effects of posture assistance on the temporal aspects of stepping performance over a series of 50 trials. The finding that the speed of first step execution remained faster than baseline immediately after posture assistance was removed, and for up to one-week post-training, suggested retention of improvements in the temporal aspects of stepping affecting bradykinetic movement.

Influence of Posture Assistance on Rapid Step Initiation

As in past studies,[10,20–22] participants with PD in the medication "on" state had a longer APA duration reflecting a postural deficit and took longer to execute the first step than healthy control subjects. The PD group also showed a general tendency for the timing sequence or temporal coordination between APA onset and step onset to be slightly longer than for controls, but this trend was not statistically different for these mildly to moderately involved individuals.

The application of a precisely timed lateral waist pull introduced in the early phase of self-triggered ML APAs, shortened the APA duration for lateral weight transfer. Compared with an earlier study[22] showing that APA duration is reduced from unassisted baseline performance with lateral postural assistance during a block of only six trials, the current study results demonstrated that comparable effects persisted across a nearly fivefold increase in trial repetitions. Thus, posture-assisted changes in APA performance are sustainable at dosage levels of 40 to 60 trials that have been previously found to promote short-term acquisition of APAs during bimanual load lifting.[35]

Furthermore, the current postural effects were accompanied by earlier step initiation onset times and faster execution times for both participants with PD and healthy controls, which also persisted over the extended acquisition trial blocks. The APAs enhance whole-body balance stabilization before and during the first step and thus potentially affect frontal plane balance control and first step ML foot placement, distance, and timing.[36] Thus, one might have expected a change in the step length with the postural assistance. However, this parameter was neither changed with the postural assistance nor different between the groups. The absence of a deficit in step length for these moderately affected participants with

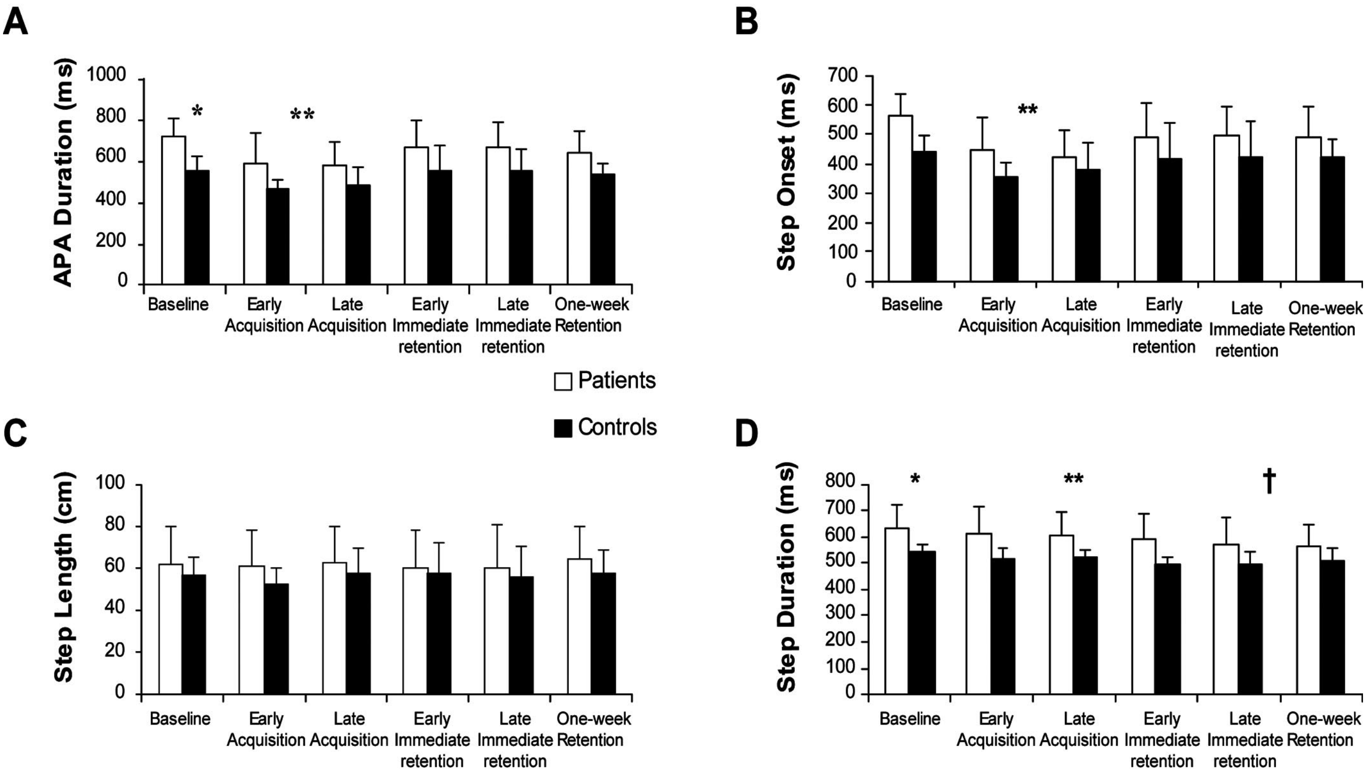

FIGURE 3. The group mean values plus 1 SD for APA duration (A), first step onset time (B), step length (C), and step duration (D) for subjects with Parkinson's disease in the medications "on" state (white bars) and healthy control subjects (black bar) bars during rapid self-paced step initiation. The experimental conditions are initial baseline trials without postural assistance, the first block of acquisition training trials with lateral postural assistance (early acquisition), the last block of acquisition training trials (late acquisition), immediate retention trials 1 to 3 without postural assistance (early immediate retention), trials 7 to 10 without postural assistance (late immediate retention), and one-week retention trials with no postural assistance. *Significant differences between groups at $P < 0.05$; **significant difference between baseline and acquisition conditions $P < 0.001$; †significant difference between baseline and immediate retention and one-week retention conditions $P < 0.001$.

PD probably accounts for the absence of step-length modification.

Capacity for Adaptive Improvements in Stepping with Posture-Assisted Training in PD

Although it is known that individuals with PD can improve the speed, accuracy, and coordination of some motor tasks with task-specific practice,[35,37] the achieved benefits are generally less pronounced or take longer to acquire than for healthy control subjects.[35,37–40] However, this indicates that participants with PD generally retain the capacity to improve aspects of movement performance through practice training. For example, recent studies found that body weight–supported treadmill training in participants with PD can improve gait speed, stride length, and cadence immediately after a single session of training.[40,41] Therefore, we reasoned that a single session of more intensive posture-assisted step training would result in immediate and short-term retention. Despite significant acquisition effects for APA duration and first step onset time, these changes were not retained. Thus, more intensive and long-term posture-assistance training may be required to produce more persistent changes. In contrast, however, first step duration, which was reduced during acquisition trials in both groups, remained significantly shorter during both immediate-retention and one-week retention trials. Because first step length was not different from baseline for any of the conditions, the subjects' first step speed was therefore faster for both groups in the same proportions.

Possible Mechanisms for Improvements in Step Initiation with Posture Assistance

Concerning the mechanisms through which improvements in posture and stepping components of step initiation may be achieved with posture assistance, it is possible that the pulling stimulus served as an external timing cue that enhanced performance. It is known, for example, that difficulty in executing particularly internally cued voluntary movements is most problematic in PD and that such movements can be improved by the presentation of external sensory cues.[1,6,20,21,42,43] External cueing has been proposed to bypass the neural pathways involving the disrupted basal ganglia output to the supplementary motor area of the cortex, which is thought to provide internal timing information for sequencing internally triggered motor subtasks.[44] In a previous study,[22] we compared posture-assist trials with a waist-tug condition that was delivered at the same location with the same timing (ie, pull onset and velocity) but used a displacement that was reduced to 25% of the acquisition waist pulls. The waist tug gave little mechanical assistance with lateral weight transfer but provided a vigorous stimulus to the pelvic area that could conceivably have been used as a timing cue to initiate stepping. No differences in the APA and stepping variables were found between baseline trials and waist-tug trials regardless of whether the waist tug immediately preceded or followed posture-assisted trials. Although the waist tug was likely a less intense stimulus than the posture-assist condition, subjects clearly perceived the waist-tug stimulus. In addition, healthy older control subjects, whose putative internal timing cue mechanism was presumably relatively intact, also improved their performance with posture assistance but not with the waist tug. Thus, the assistance with achieving anticipated postural state conditions involving the position and motion of the COM relative to the changing base of support configuration, more likely contributed to the faster onset timing of the gait cycle than the mere presence of an external timing cue.

It is also possible that the predictable timing delivery of the lateral waist pull during the APA performance helped subjects to better focus their attention on task performance.[44] Alternatively, the imposition of the waist pull assist concurrent with subjects' efforts to initiate stepping might also have distracted their attention from the goal intended task. The current study does not rule out the former possibility but argues against task interference.

Although we did not specifically examine whether step practice without postural assistance might account for the present findings, a previous investigation suggested that the effects of the acquisition condition were not likely attributable to practice alone.[22] In that study, when blocks of trials without postural assistance immediately followed acquisition trials that demonstrated improved APA and step characteristics over baseline, the unassisted trials did not vary from baseline. Hence, strict practice effects were not apparent. However, it might be that the increased number of trial repetitions used in the current study was more compatible with practice related improvements in performance.

Limitations of the Study

Among the limitations of this study is the focus on participants with early-stage PD, so that the findings may not be generalizable to individuals with more severe disease. The use of a relatively small sample size might have masked potential carryover effects of posture-assisted training on APA and stepping performance. There is a need to identify whether comparable or more robust changes in stepping performance can be achieved for more severely affected participants demonstrating greater deficits in posture and gait performance including freezing of gait. Another limitation was that participants with PD were only tested in the medications "on" state. Although the current study results were similar to those of a previous study[22] involving comparably involved participants with PD tested in the medications "off" state, it would be important to know the extent to which such adaptive changes in stepping performance are dependent on dopaminergic mechanisms by directly comparing the effects of training in the medications "on" and "off" conditions for the same group of subjects. A further limitation is the need to more directly determine the extent to which practice training without postural assistance might contribute to the results. Furthermore, the retention effects on step execution timing found after a single training session might not be comparable during a longer training period. It also remains to be determined whether a long-term postural assistance intervention approach can lead to persistent improvements in gait initiation performance in individuals with PD.

SUMMARY

In summary, the results of this study indicated that short-term acquisition improvements in temporal aspects of rapid gait initiation, including a shorter APA duration, earlier first step onset time, and shorter first step duration, are possible with a single session of posture-assisted step training in people with mild to moderate PD studied in the medications "on" state. It is encouraging that the adaptive changes in the speed of stepping were retained immediately and for as long as one week after training. This indicates that the capacity of participants with PD to potentially benefit from more intensive longer duration posture-assisted training.

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