TITLE:
The Interaction of Postural and Voluntary Strategies for Stability in Parkinson's Disease

Authors:
Andrea C. de Lima-Pardini¹,², Selma Papegaaij¹,³, Rajal G. Cohen¹,⁴, Luis A. Teixeira²,
Beth A. Smith¹, and Fay B. Horak¹,
¹Department of Neurology, Oregon Health & Science University, 3181 SW Sam Jackson
Park Road, Portland, Oregon 97239-3098, United States
²Human Motor Systems Laboratory, School of Physical Education and Sport, University
of São Paulo, São Paulo, SP, Brazil
³Center for Human Movement Sciences, Faculty of Medical Sciences, University of
Groningen, Groningen, the Netherlands
⁴Department of Psychology and Communication Studies, University of Idaho, Moscow,
Idaho 83844-3043, United States

Author contribution:
A.P. - conception and design of research, performed experiments, analyzed data,
interpreted results of experiments, prepared figures, drafted manuscript, edited and
revised manuscript.
S.P. - design of research, performed experiments, analyzed data, interpreted results of
experiments, prepared figures, approved final version of manuscript.
R.C. - design of research, analyzed data, interpreted results of experiments, revised
manuscript, approved final version of manuscript.
L.T. - design of research, interpreted results of experiments, revised manuscript, approved final version of manuscript.

B.S. - design of research, interpreted results of experiments, revised manuscript, approved final version of manuscript.

F.H. – laboratory and grant resources, design of research, analyzed data, interpreted results of experiments, revised manuscript, approved final version of manuscript.

Running head: Interaction of postural and voluntary strategies in PD

Correspondence to:
Andrea C. de Lima-Pardini
Av. Prof. Mello de Moraes, 65 - Cidade Universitária, CEP: 05508-030 - São Paulo – SP, Brasil.
Email: aclfisio@yahoo.com.br
ABSTRACT

This study assessed the effects of stability constraints of a voluntary task on postural responses to an external perturbation in subjects with Parkinson’s disease (PD) and healthy elderly participants. Eleven subjects with PD and 12 control subjects were perturbed with backward surface translations while standing and performing two versions of a voluntary task: holding a tray with a cylinder placed with the flat side down (low constraint - LC) or with the rolling, round side down (high constraint - HC). Participants performed alternating blocks of low and high constraint trials. Parkinson’s disease participants accomplished the voluntary task as well as controls, showing slower tray velocity in the high, compared with the low, constraint condition. However, the latency of postural responses was longer in the high constraint condition only for control subjects. Control subjects presented different patterns of hip-shoulder coordination as a function of task constraint whereas PD subjects had a relatively invariant pattern. Initiating the experiment with the high constraint task led to (a) decreased postural stability in PD subjects only, and (b) reduced peak hip flexion in control subjects only. These results suggest that Parkinson’s disease impairs the capacity to adapt postural responses to constraints imposed by a voluntary task.

Keywords: postural control, postural set, initial condition
INTRODUCTION

Postural responses to unexpected stance perturbations are considered to be automatically controlled. Automatic movements are triggered by external cues and carried by polysynaptic pathways within the spinal cord and brainstem; they are of shorter latency than voluntary movements and are hard to suppress at will (Prochazka et al. 2000). Nevertheless, recent studies have found that automatic postural responses can be influenced by cortical processing associated with learning, prior experience and initial postural conditions (Jacobs and Horak 2007 for review). In addition, we recently showed that postural responses can be modulated by constraints set by a concomitant voluntary task (de Lima et al. 2010).

Our recent findings support the notion that a higher order level of motor control, “postural set” as proposed by Prochazka (1989), modulates automatic postural responses based on context set by the manual task. We tested the effects of a manual, voluntary task constraint on postural responses to unexpected motion of the support surface by requiring stabilization of an unstable (rolling) cylinder on a tray (de Lima, et al. 2010). Results showed that the constraint imposed by the manual task led to early postural muscle activation and reduced joint motion in the legs. This adaptation of postural responses was paralleled by decreased tray displacement, indicating a two-way interaction between posture control and voluntary control of the arms (for further evidence of postural and voluntary task interaction see also Chen et al. 2011; Morioka et al. 2005; Stoffregen et al. 1999; Stoffregen et al. 2000; Wulf et al. 2004; Wulf et al. 2003; Yu et al. 2010).
Previous studies in our laboratory have suggested that modulation of postural responses based on context is impaired by Parkinson’s disease (PD) (Chong et al. 1999b, 2000; Chong et al. 1999c; Horak et al. 1999; Rocchi et al. 2002). Individuals with PD do not promptly adjust the magnitude of their postural responses based on their initial posture (Horak et al. 1999; Rocchi et al. 2006), direction of perturbation (Chong et al. 1999a), instructional set (Chong et al. 1999a; Chong et al. 1999b, 2000) or prior experience (Chong et al. 1999a; Chong et al. 2000; De Nunzio et al. 2007). Of particular interest for the present study, individuals with PD have been found to be impaired at integrating control of postural stability with the goal of voluntary tasks such as step initiation (Burleigh-Jacobs et al. 1997; Gantchev et al. 1996; Rocchi et al. 2006), trunk bending (Alexandrov et al. 1998), and pointing to a target (Tagliabue et al. 2009). Tagliabue et al. (2009) showed that as the stability constraint imposed by a pointing task increases, functional integration between the voluntary and postural tasks decreases in individuals with PD. The high stability constraint condition led to poorer control of the center of body mass in subjects with PD whereas performance on the voluntary task was unaffected (Tagliabue et al. 2009).

Although the integration between postural and voluntary task control has already been investigated in people with Parkinson’s disease (Alexandrov et al. 1998; Burleigh-Jacobs et al. 1997; Gantchev et al. 1996; Rocchi et al. 2006; Tagliabue et al. 2009), questions remain about how postural responses to an external perturbation adapt to changes in the voluntary task constraint. Previous studies focused on integration of self-initiated postural movements, rather than externally triggered postural responses. As a neurophysiological question, our experiment is important for understanding interactions
between different levels of movement control (automatic and voluntary). In addition, our
study addresses an important question related to the flexibility of postural reactive
responses in PD participants associated with voluntary task constraints. Recent studies
have highlighted higher fall incidence in patients with PD under conditions in which a
voluntary task is accomplished during unexpected external perturbation (Bloem et al.
2001; Grimbergen et al. 2004; Smithson et al. 1998; Willemsen et al. 2000), but the
neurophysiological basis for this difficulty is not understood.

We assessed postural responses to backward surface translations while a
manual, voluntary task was performed in the context of either a high or low stability
constraint. Postural responses were assessed through latency of muscular activation
and center of body mass stability. Onset of muscle activation was used as an indicator
of modulation of postural responses by central set. Since the onset of muscular
activation occurs at an early phase of postural control, it indicates whether adjustments
have been made in a feedforward manner based on the initial constraints of the
voluntary task. We predicted increased latencies of postural muscle responses under
the high voluntary task constraint in healthy elderly participants, due to cortical
influences on postural control, and no change of postural response latencies in PD
participants based on task constraint. As a consequence, we expect PD participants to
show decrements in postural stability under the high constraint voluntary task.
Kinematics of the lower limbs was used to assess adjustments in postural strategy in
later phases of postural control. Adaptability from previous experience was assessed
through repetitive perturbations under the same task constraint, while adaptability to
context change was assessed through transitions between task constraints.
METHODS

Subjects

Eleven subjects with idiopathic Parkinson’s disease (5 males, 6 females; mean age 67.2 ± 5.5 yr) and 12 age-matched healthy control subjects (6 males, 6 females; mean age 68.0 ± 5.0 yr) participated in this study. The diagnosis of idiopathic PD was made by a movement disorders neurologist. Mean illness duration of PD participants was 8.3 yr (± 3.3, range 5-14). Mean score on the Unified Parkinson’s Disease Rating Scale (Fahn et al. 1987) was 27.5 (± 9.4, range 17.5-46), and mean Hoehn and Yahr stage (Hoehn and Yahr 1967) was 2.7 (± 0.5, range 2-3). General cognitive function was assessed for both groups with the Montreal Cognitive Assessment (Nasreddine et al. 2005) (PD: mean 27.4 ± 1.8; controls: mean 27.9 ± 1.5). One participant in the PD group was excluded due to a low score (20) on the cognitive assessment. All participants were tested without pain or other conditions limiting independent stance, and all had vision corrected to 20/40 or better.

Participants with PD were tested while taking their anti-PD medication (ON levodopa state) for two reasons. First, patients with PD are likely to show tremor and bradykinesia of the upper limbs in the OFF medication state, which could impair their voluntary performance of balancing the cylinder on the tray. Second, unlike the effects on voluntary control, the ability to change postural responses based on the context has been shown not to improve with medication in Parkinsonian patients (Bloem et al. 1996; Horak et al. 1996). All participants provided informed consent, and experimental
procedures were approved by the Oregon Health and Science University Institutional Review Board.

**Apparatus and Task**

Participants performed a dual task of upright standing on a movable force plate while holding a wooden tray (30 cm x 40 cm, mass 432 g) with a cylinder (diameter 9.5 cm, height 5 cm, mass 124 g) on it. The upper arms were to be maintained parallel to the trunk, and elbows were bent at 90 degrees (Fig. 1). The aim of the postural component of the task was to maintain stable upright stance while the force plate was unpredictably moved 11 cm backward, with mean velocity of 16 cm/s and peak acceleration of 12 cm/s². The aim of the manual component of the task was to maintain a cylinder stably at the middle of the tray during force plate motion.

**Experimental design**

Both PD and control groups were evaluated in two conditions, low and high constraint. In the low constraint condition (LC) the cylinder was lying on its flat side, so that slow horizontal movements of the tray would not lead to a slide of the cylinder on the tray (Fig. 1, left panel). In the high constraint condition (HC), the cylinder was placed on its round surface, so that it was free to roll in the anterior-posterior direction, limited in motion to around 90 degrees by a weight attached to its bottom (Fig. 1, right panel). The heavier the weight, the easier it is to prevent cylinder motion. In order to find the most challenging situation within individual limitations, subjects were asked to try to prevent the cylinder from moving while holding the tray, starting with a weight of 10g.
(most challenging). The weight was increased by steps of 10g up to the weight at which
the participant could equilibrate the tray with the cylinder on it in three consecutive
periods of 10s. This procedure was done in order to achieve approximately the same
challenge in high constraint condition for all participants.

The experimental protocol consisted of 3 blocks of 7 trials in each task constraint
level, for a total of 42 trials. Low and high constraint trial blocks were alternated, with the
first constraint condition counterbalanced across subjects. Repetition of trials in the
same task constraint allowed assessment of adaptability with practice, while alternation
of different conditions between blocks allowed assessment of adaptability to a change.

Procedures

Participants wore a harness attached to the laboratory ceiling, and an assistant
stood near the participant to assist in cases of loss of balance. The following
instructions were given to participants: “Stand straight with your upper arms parallel to
your body and your elbows at 90 degrees and look at the cylinder. The platform will
move backward. We will not tell you to get ready, so you will not know exactly when the
perturbation will start. Please, keep looking at the cylinder and try to avoid any
movement of the cylinder. Also, try to do not step during the perturbation.” Additionally,
participants were asked to maintain the same balance of pressure on the ground
beneath their feet, which was monitored on an oscilloscope by the experimenter
immediately before triggering each force plate displacement. Participants were asked to
place their feet in a comfortable position (mean 13.4 ± 2.6 cm apart). Foot positions were marked with tape to make sure the same position was maintained throughout the experiment. On finishing each trial, participants gave the tray back to experimenter and waited on the platform during its automatic (slow) repositioning. When the initial position was achieved, the tray was given back to the participant and the cylinder repositioned for the next trial. Rest breaks lasting 1 min. were given between blocks. After three blocks, a longer rest was allowed, during which participants were sat for 15 minutes. No refamiliarization was provided between blocks.

Data collection and analysis

Electromyographic (EMG) activity was measured from the medial heads of the right gastrocnemius (GAS) and tibialis anterior (TA) muscles, using 2.5 cm surface electrodes attached 2-4 cm apart. The skin was shaved, cleaned and scrubbed prior to application of the electrodes. Online, EMG signals were amplified at a gain of 2000–10000, band-pass filtered from 15–2000 Hz, and sampled at 480 Hz. Offline, they were rectified and low-pass filtered at 10 Hz. Center of pressure (CoP) position over time was sampled from the force plate with a sample frequency of 480 Hz and filtered at 10 Hz. A motion analysis system with eight Falcon video cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) provided 3D coordinates of the reflective markers on the body, tray, cylinder and movable surface, sampled at 60 Hz. Reflective markers were placed bilaterally at the fifth metatarsophalangeal joints, heels, lateral malleoli, lateral knee joint centers, greater trochanters, acromions, lateral epicondyles, wrist joint centers and jaw joint centers. Additional markers were attached at the moving platform
and the steady floor as reference to define the platform movement. Twenty-six anthropometric measures of head, limb, and trunk segments (length, width, and perimeter) were collected from each participant (Chandler et al. 1975). These anthropometric measures, together with the motion analysis data, were used to estimate the sagittal plane center of body mass (CoM).

Measurements

Peak tray velocity was used to compare performance of the voluntary task between the LC and HC conditions. Low peak tray velocity was interpreted as better performance on the voluntary task, since this variable was positively correlated (r=0.68) with the total path of the cylinder marker in the HC trials.

Postural reactive responses were quantified by latency of the GAS and TA muscles activation. The onsets of muscle bursts were identified as the first sustained EMG activity (> 25 ms) greater than two standard deviations above the baseline.

Postural equilibrium was quantified by two variables: automatic postural response stability (APR) and magnitude of the first CoM peak. The APR was calculated by integrating the difference (normalized to participant height) between the CoP and CoM time-series over 150 ms, starting 50 ms after the onset of the first GAS burst (agonistic muscle). The APR provides a measure of the margin of stability, showing the force generated by the postural response to arrest the falling CoM (Winter et al. 1998), with high values being interpreted as increased postural stability.

Interaction between the voluntary and postural tasks was characterized by coordination between the shoulder and hip joints. Interjoint coordination was assessed
by fitting an ellipse embracing 95% of the values of the angle-angle plot for the hip and
shoulder joints displacement from the perturbation onset until the end of the trial. First,
we calculated the ratios of the short axis vs. the long axis of each ellipse. This variable
was used to detect different modes of coordination between the joints in two ways.
Second, we conducted regression analysis to find the slopes of the fitted ellipses.
Higher slopes indicate relatively larger participation of the hip joint, and lower values
indicate relatively larger participation of shoulder joint.

Relative phase between shoulder and hip joints was calculated with the Cross
Spectral Density method (Duarte, 2002; Bennett et al. 2005). The values of relative
phase ranged from 0 to 180 degrees. Values around 0 degrees correspond to in-phase
coordination, values around 180 degrees correspond to anti-phase coordination, and
values that are not close to 0 or 180 degrees indicate to out of phase coordination.

**Statistical analysis**

Adaptation across blocks was measured for all variables, comparing the
averages obtained in the first block with the last block of trials. Preliminarily, data were
analyzed through four-way 2 (group) x 2 (sequence: low-high [L-H] x high-low [H-L]) x 2
(constraint: HC x LC) x 2 (block: first x last) ANOVAs with repeated measures on the
last two factors. Results showed an absence of a block effect except for shoulder and
peak hip flexion. For this reason, the other variables were analyzed through three-way 2
(group) x 2 (sequence) x 2 (constraint) ANOVAs with repeated measures on the last
factor. The level of significance was set at 0.05. Post hoc comparisons were made
through the Tukey test. Only significant effects will be reported.
RESULTS

Tray velocity

Figure 2 depicts average tray velocity curves for control (panels A and B) and PD (panels E and F) participants. Tray velocity was not different between groups. The main effect of constraint was significant \([F(1,20) = 63.08, p = 0.01]\), due to reduced tray velocity in the HC condition (mean 16.36 ± 0.86 cm/s) than in the LC condition (mean 12.10 ± 0.72 cm/s). In the Fig. 3A, group average values are compared as a function of task constraint and sequence.

Postural muscle latency

The TA muscle latency showed a significant main effect of constraint \([F(1,20)= 6.21, p = 0.02]\), with later activation in the HC (mean 134.22 ± 7.02 ms) than the LC condition (mean 123.47 ± 6.82 ms). Although analysis did not indicate a significant group by constraint interaction, Fig. 3B suggests that task constraint affected the control group more than the PD group. For this reason, we performed a two-way ANOVA with 2 groups and 2 constraints. Analysis showed significant interaction \([F(1,22)=6.68, p = 0.02]\) due to higher TA latency in the high constraint condition than in the low constraint condition for the control group but not for the PD group. The GAS muscle latency was not affected by constraint or order.

Fig. 2 about here
Postural stability

APR CoP-CoM stability curves are depicted in Fig. 2 for control (panels C and D) and PD (panels G and H) participants. Stability was significantly affected by group [\(F(1,20) = 8.60, p = 0.008\)], sequence [\(F(1,20) = 4.39, p = 0.04\)] and group by sequence interaction [\(F(1,20) = 5.40, p = 0.03\)]. APR stability was lower in the H-L sequence than in the L-H sequence for the PD group, while no significant difference was detected for the control group (Fig. 3C).

Hip-shoulder coordination

Representative examples of shoulder-hip joint angle plots are shown in Fig. 4A. Analysis of the ellipse slope indicated a significant main effect of constraint [\(F(1,20) = 13.60, p = 0.001\)] and a group by sequence interaction [\(F(1,20) = 5.46, p = 0.03\)]. The H-L sequence was associated with a smaller slope than the L-H sequence in controls, while no significant difference was found between sequences for PD participants (Fig.4B).

Inter-joint coordination of hip and shoulder displacement during the task was objectified with ellipse ratios. A significant main effect of sequence [\(F(1,20) = 5.60, p = 0.03\)] and a group by sequence interaction [\(F(1,20) = 4.55, p=0.04\)] were found for ellipse ratios. Higher values for the H-L than the L-H sequence for the control group were found, while no significant difference was found between sequences for PD participants (Fig.4C).

Relative phase between the shoulder and the hip is represented in Fig. 4D. Analysis indicated a significant main effect of constraint [\(F(1,20) = 17.14, p < 0.01\)] and
a group by constraint interaction \[F(1,20) = 12.33, p < 0.01\]. The control group showed out of phase coordination in HC (mean 74.20 ± 15.90 deg) compared to in-phase coordination in LC conditions (mean 7.70 ± 1.34deg), while the relative phase in the PD group did not significantly differ according to voluntary task constraint level (LC mean = 10.80 ± 2.23 deg; HC mean = 13.53 ± 6.61 deg).

**Adaptation across blocks**

Figure 5A shows adaptation curves of peak shoulder flexion as a function of sequence of task constraints. Shoulder flexion adapted over time as shown by a significant main effect of block \[F(1,40) = 32.26, p < 0.01\]. Post hoc comparisons indicated smaller values of peak shoulder flexion in the last block than in the first block. The difference between the groups of the rate of adaptation of shoulder peak flexion was more subtle than for peak hip flexion, with control subjects reducing values across time by 39% and PD subjects reducing values by 31%. Although analysis did not indicate a significant group by constraint interaction, Fig. 5A suggests that task constraint had a stronger effect on the control group, which shows larger shoulder flexion in HC conditions than in LC conditions.

Figure 5B shows adaptation curves of peak hip flexion as a function of sequence of task constraints. Analysis indicated significant main effect of group \[F(1,40) = 5.82, p = 0.02\], sequence \[F(1,40) = 10.84, p < 0.01\], and block \[F(1,40) = 32.07, p < 0.01\], in addition to significant group by sequence \[F(1,40) = 18.15, p = 0.002\] and group by block interactions \[F(1,40) = 10.29, p < 0.01\]. The H-L sequence resulted in smaller hip
flexion than the L-H sequence for the control, but not the PD group. Post hoc comparisons for the effect of block indicated smaller hip flexion in the last block, compared to the first block. Control participants decreased hip flexion across time by 54%, whereas PD participants decreased hip flexion by only 18% from the first to the last trial.

DISCUSSION

This study examined the effects of stability constraint imposed by a voluntary task (balancing an object on a tray) on postural responses in individuals with Parkinson’s disease (PD) compared with age-matched healthy participants. Results showed that the stability constraint from the voluntary task affected performance of both voluntary and postural tasks in the two groups, but less effectively in the PD group. In the voluntary task, both groups showed decreased tray velocity and increased participation of shoulder movements in response to perturbations during the high constraint task, as seen by a change in shoulder-hip relationship. In contrast, the latency of postural muscle activation increased in high constraint conditions in control subjects but not in PD subjects. These results suggest that PD leads to a decreased capacity to adjust postural control for constraints imposed by a voluntary task.

Subjects with Parkinson’s disease also showed a significant inability to flexibly change kinematic strategy based on constraints imposed by a voluntary task and by prior experience. Sequence of task presentation and varying stability constraint context, led to different coordination modes between hip and shoulder involved in the postural
Voluntary task performance and its integration with postural responses

Parkinson’s disease and control participants achieved the voluntary task goal of minimizing cylinder motion by reducing tray velocity under the high task stability constraint. Kinematics analysis showed that the PD and control groups both reduced tray velocity by increasing participation of the shoulder in stabilizing the tray under the high constraint context. In contrast, previous studies in individuals with PD have shown poor voluntary task performance in challenging tasks, such as tasks imposing time pressure (Doan et al. 2006; Tunik et al. 2004) or high accuracy demand (Rand et al. 2000; Weiss et al. 1997). Our PD participants, however, kept an adequate performance in the voluntary task associated with decreased postural control. Considering that controls and PD participants did not differ in voluntary task performance one could assume that it was possible to achieve cylinder stability by adopting either the kinematic strategy showed by the control subjects or the one showed by the PD subjects. However, PD subjects performing the H-L sequence suffered decreased postural stability, suggesting that they used a less than optimal postural strategy.

The finding of appropriate voluntary movement adjustments in PD subjects might be surprising. A possible explanation is that motion of the arms to stabilize the cylinder
may have been triggered by sensory stimuli from vestibular and proprioceptive receptors signaling loss of stable balance from the abrupt platform motion. Previous studies have shown that PD participants use external cues to trigger difficult voluntary movements (Darmon et al. 1999; Gueye et al. 1998; Kelly et al. 2002). In this regard, additional sensory information derived from postural perturbation might have been used to facilitate a voluntary task under different constraints. An alternative explanation is that voluntary performance in PD subjects was ameliorated by taking levodopa (Haslinger et al. 2001; Kelly et al. 2002; Rascol et al. 1994). Our participants were under the effect of levodopa, which has been shown to be of greater benefit for voluntary behavior than for postural control (Bloem et al. 1996; Horak et al. 1996; Horak et al. 1992). From these results, it is apparent that voluntary control during postural perturbations is not disturbed in individuals with PD in the ON levodopa state.

In contrast to voluntary control subjects, PD subjects were found here to have impaired ability to adapt postural responses from voluntary task constraints. Control, but not PD, subjects delayed the latency of their TA activation in response to postural perturbation based on the voluntary task constraint. That behavior supports our hypothesis of modulation of postural responses from higher order, feedforward, central set in control subjects, but not PD subjects (Jacobs and Horak 2007). These results are consistent with previous findings indicating that individuals with PD have a reduced ability to immediately adjust postural responses to context based on feedforward control (Chong et al. 1999a; Chong et al. 1999b, 2000; Haslinger et al. 2001; Horak et al. 1992). Our results thus support a disruption of the interaction between voluntary actions
and automatic postural responses in individuals with PD, consistent with a loss of the ‘posture first’ strategy seen in healthy subjects (Bloem et al. 2006).

Influence of the constraint sequence

We found that the sequence of task constraints affected kinematics (peak hip flexion) and coordination (shoulder-hip ratio) of postural and voluntary task control in the control group. Kinematic strategies, on the other hand, were not affected by current task constraint. Our results showed that once a shoulder-hip coordination mode and hip strategy is selected by the central nervous system to accomplish both the postural and voluntary tasks, it is maintained across constraint conditions. Generalization of postural strategies has also been seen in situations in which people are exposed to discrete, unpredictable postural perturbations, like in a push or slip. In those situations, individuals generate motor responses which tend towards a default value corresponding to a medium-sized perturbation (Horak et al. 1989) or to a size appropriate to withstand the largest perturbation (Van Ooteghem et al. 2008; Van Ooteghem et al. 2010; Van Ooteghem et al. 2009). Previous studies have also shown that for sequences of similar voluntary actions individuals often reuse a motor plan rather than generating a new one (Cohen and Rosenbaum 2004; Rosenbaum et al. 2001). It has been suggested that this strategy is more computationally efficient (even if less biomechanically efficient), and might be used in postural control.

Unlike controls, PD subjects were insensitive to sequence of task constraints. We presented evidence that PD participants were unable to adjust the shoulder-hip mode of coordination and hip strategy in accordance with the sequence of voluntary task
constraint. This behavior highlights the reduced flexibility of PD individuals to generate appropriate motor responses under different contexts. This assertion is strengthened by the finding that in the PD group postural stability was lower in the H-L sequence than in the L-H sequence. Previous studies have shown that performance in challenging voluntary tasks leads to decreased postural stability in individuals with PD whereas no influence on voluntary task performance was observed (Bloem et al. 2006; Marchese et al. 2003; Tagliabue et al. 2009). A possible explanation for that behavior is that, under challenging conditions, PD individuals prioritize the voluntary task over postural control (Bloem et al. 2006). It is plausible that individuals with PD allocated more neural resources to accomplish the voluntary task, leading to deteriorated postural control, while healthy individuals implement a more balanced distribution of resources between voluntary and manual tasks. Alternatively, the less effective postural control demonstrated by the PD group could have been caused by a loss of ability to flexibly adopt different modes of coordination, and by reduced hip mobility.

**Adaptation of postural kinematics**

In agreement with prior studies showing gradual reduction of postural responses after repetitions of the perturbation (Keshner et al. 1987; Timmann and Horak 1997; Van Ooteghem et al. 2009), our results showed that control subjects gradually decreased hip and shoulder flexion across blocks of trials. Decreasing magnitude of postural responses across trials is thought to be a result of habituation, leading to increased energy efficiency (Horak and Nashner 1986; Keshner et al. 1987). Depending on the sequence, the control group showed different participation of the hip, starting at
the very first block. Control participants who started with the high constraint condition used less hip flexion and adapted faster than those who started with the low constraint condition. In contrast to the sequence effect on hip flexion, control subjects modulated use of shoulder movements depending on the current constraint from the voluntary task. That shoulder behavior as a function of constraint condition is consistent with results from our relative phase analysis. Unlike PD subjects, controls adapted the coordination mode between the hip and shoulder to the voluntary task constraint: controls showed interjoint coordination closer to an in-phase mode of coordination in the low constraint condition and closer to an out-of-phase mode in the high constraint condition. Since each joint motion was affected by different factors (hip by prior experience and shoulder by current context), shoulder (voluntary movement) and hip joints (postural control) may be controlled by separated neural mechanisms (Torres et al. 2011).

Subjects with PD showed neither a sequence-effect for the hip nor a constraint-effect for the shoulder kinematics or for relative phase of the hip-shoulder motions. The same behavior of shoulder and peak hip flexion regardless of current constraint condition or task sequence in the PD group supports the notion of reduced flexibility in adapting postural responses based on central set. Altogether, our findings indicate that healthy elderly subjects are able to modulate postural responses consistent with stability constraints imposed by a voluntary task, whereas Parkinson’s disease leads to decreased adaptability of postural control to deal with voluntary task constraints. This decreased adaptability may be harmful to maintenance of upright stance when unpredictable postural perturbations occur during performance of voluntary tasks.
ACKNOWLEDGMENTS

We thank all the participants, Elizabeth Murdock for recruiting subjects, Marina Brito Silva for data collection assistance, Edward King for technical assistance and Patty Carlson-Kuhta for general assistance. This research was supported by grants from NIH (R37AG006457 awarded to F.B. Horak) and from the Brazilian National Council for Scientific and Technological Development (CNPq) (200321/2010-2) awarded to A. C. de Lima-Pardini.
REFERENCES


http://demotu.org/software2/relphase.m [2012]


FIGURE CAPTIONS

Fig. 1. Experimental setup. Schematic representation of the experimental setup for the low (LC) and high (HC) constraint conditions. In the picture on the right, the subject is bending forward to indicate the hip and shoulder angles. Small circles represent kinematic markers. Horizontal arrows indicate direction of surface translation.

Fig. 2. Grand means of tray velocity and difference between COP and COM, representing postural stability for control (A-D) and PD (E-H) participants. A, C, E, and G show means for participants performing the L-H sequence, B, D, F, and H show means for participants performing the H-L sequence. Dashed lines represent the low
constraint current condition and solid lines the high constraint current condition. Arrows indicate forward direction. Shaded areas represent the region below the COP-COM curve taken to calculate the margin of stability.

Fig. 3. Postural and voluntary performance. Averages and standard errors across subjects for (A) tray velocity, (B) TA latency, and (C) margin of stability for current constraint and constraint sequence for PD and control groups (high values are interpreted as increased postural stability).

Fig. 4. Interjoint coordination for PD and control participants as a function of current constraint and sequence of constraints. (A) Representative examples of shoulder and hip coordination of 21 trials for control subjects 4 (L-H sequence) and 5 (H-L sequence), and for PD subjects 6 (L-H sequence) and 4 (H-L sequence). (B) Mean and standard error of the ellipse slope. (C) Mean and standard error of the ratio of ellipse. (D). Relative phase between shoulder and hip (high values are interpreted as more out of phase coordination).

Fig. 5. Peak joint flexion for PD and control participants as a function of current constraint and sequence of constraints. A. Shoulder flexion. B. Hip flexion. Shaded squares represent the HC conditions and white squares represent the LC conditions.