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Abstract

Stability improvements made in a single acquisition session with merely 5 slips in walking are sufficient to prevent backward balance loss (BLOB) at the end of session, but not after 12 months. The purpose of this study was to determine whether the effect of an enhanced single acquisition session would be retainable if tested sooner, at intervals of up to 4 months.

Twenty-four young subjects were exposed to blocks of slip, non-slip, and both types of trials during walking at preferred speeds in the acquisition session. In each of the 4 follow-up sessions around 1 week, 2 weeks, 1 month and 4 months later, these same subjects experienced only a single slip following 8-13 unperturbed walking trials in an otherwise identical setup. Gait stability was obtained as the shortest distance between the measured center of mass (COM) state (position and velocity) and the mathematically predicted threshold for BLOB at pre- and post-slip, corresponding to the instants of touchdown of the slipping limb and liftoff of the contralateral limb, respectively. During the acquisition session, pre- and post-slip stability improved significantly, resulting in a reduction of BLOB from 100% in the first slip (S1) to 0% in the last slip (S24), with improvements converging to a steady-state, that enabled all of the subjects to avoid BLOB, regardless of whether a slip occurred or not. During retest sessions, subjects’ pre-slip stability was not different from that in S24, but was greater than that in S1. Their post-slip stability was also greater than in S1 but less than in S24, resulting in BLOB at a 40% level. No difference was found in any of these aspects between each follow-up session. These adaptive changes were associated with a range of individual differences, varying from no detectable deterioration in all aspects (n = 8) to a consistent BLOB in all follow-ups (n = 3). Our findings have demonstrated the extent of plasticity of the central nervous system, characterized by rapid acquisition of a stable COM state under unpredictable slip conditions and retention of such improvements for months, resulting in a reduced occurrence of unintended backward falling.
Introduction

An essential function of the central nervous system (CNS) is to retain appropriate motor behavior that can avoid unintended falling. As a prerequisite of achieving this objective, humans are adaptable to sudden or unexpected changes in environmental constraints, occurring during different activities, as in standing or locomotion. Such motor learning can be defined as a set of internal processes occurring with practice, training and experience, resulting in relatively permanent changes in behavior. The ability of the CNS to adapt to different types of perturbations and support surface characteristics (Diener et al. 1988; Horak and Nashner 1986; Horak et al. 1989; Mummel et al. 1998; Nashner 1982; Nashner 1976), through modulation of both feedforward and feedback mechanisms (Cham and Redfern 2002; Horak and Nashner 1986; Nashner 1976; Pai et al. 2003; Pavol and Pai 2002; Pavol et al. 2004) is well established. These adjustments to repeated perturbations during stance (Fransson et al. 2002; McIlroy and Maki 1995; Nashner 1976) or gait (Bhatt et al. 2005b; Cham and Redfern 2002; Marigold and Patla 2002; Rand et al. 1998) reflect an individual’s adaptability in stability control within the CNS, however temporary it might be.

Stability control can be characterized as the control of the relative motion state (position and velocity) between the body center of mass (COM) and its base of support (BOS). Recent studies based on inducing slips during the task of sit-to-stand have suggested that repeated exposure to such perturbations can be used to adaptively improve one’s COM state stability, and subsequently reduce the likelihood of balance loss and fall (Pai et al. 2003; Pavol and Pai 2002). Similarly, repeated exposure to forward slips during walking has been shown to result in adaptive improvements of gait stability and a subsequent reduction in incidence of backward balance loss. With such training, the subjects were able to control and reduce the BOS perturbation intensity, and hence the relative motion of the COM, replacing the protective stepping response with either a “skate-over” or “walkover” strategy under the existing low friction conditions (Bhatt et al. 2005b). Though such training paradigms could make critical contributions to fall prevention, their ecological values would be limited if these adaptive effects do not lead to long-term retention.
Unfortunately, the retention of such short-term adaptive changes within the stability control system is not well understood. Recently, Tjernstrom and associates (Tjernstrom et al. 2002) demonstrated retention of the acquired changes in magnitude of body sway to calf vibrations during stance of up to one-month. In contrast, others found no “long-term” (5 days) retention of the acquired adaptation in “postural response size” (amplitude of gastrocnemius EMG) to a session of repeated “toes-up” platform rotations on the 5 consecutive sessions each spaced a day apart (Schwabe et al. 2004). Such differences may relate to the nature of the stimulus and the intensity of training used to induce the adaptation as well as the underlying neural control mechanisms.

Adaptive changes in stability control can be shown in proactive adjustments, which occur before or in anticipation of perturbation onset and rely predominantly on feedforward control. Similarly they can occur in the reactive response, which relies on feedback mechanisms, at least initially with novel perturbation, and are later possibly modulated by feedforward control. Our recent findings indicated that subjects were able to retain the acquired pre-slip stability improvements 12 months later, which were related to feedforward control, but not necessarily to post-slip stability in reactive response, which was possibly related to the feedback mechanisms (Bhatt and Pai 2005). Consequently, a single acquisition session consisting of merely 5 repeated slips in walking is sufficient at the end of session, to prevent backward loss of balance, but this is not the case after 12 months. Although the only instruction they received throughout the original acquisition and the re-test sessions was “a slip may or may not occur”, subjects were able to rapidly refresh their motor memory, demonstrating faster adaptation than the acquisition session in avoiding falling. Such evidence supports the possibility of ongoing structural changes within the CNS, enabling the conversion of temporary sensorimotor associations into long-sustaining motor programs. Nevertheless, it is imperative to determine, whether such training effects are retainable subsequently on the first slip re-exposure, with a more intense acquisition session and at shorter re-evaluation intervals than that of the previous study (Bhatt and Pai 2005).

The purpose of this study was to determine the effects of an enhanced single acquisition session at intervals shorter than 12 months. We extended the “repeated slip paradigm” (Bhatt
et al. 2005b) to include a greater number of trials and a combination of blocks of slip, non-slip and both types of trials during self-selected walking. We hypothesized that during the acquisition session, subjects would rapidly improve their pre- and post-slip stability and later reach a steady state, regardless of whether a slip occurs or not, resulting in significantly reduced incidence of balance loss as compared to the first exposure. When re-tested 1 week, 2 weeks, 1 month, and 4 months later, we hypothesized that they would exhibit a significantly greater pre- and post-slip-onset stability and a lower incidence of balance loss as compared to the first slip exposure at the acquisition session. In addition, we also hypothesized that they would retain the effects of a single session, such that their stability and the incidence of balance loss at the retest sessions would not significantly differ from the last exposure of the acquisition session.

Methods

Subjects. Twenty-four healthy young subjects (25.4 ± 5.9 years, 12 males) participated in the study after being screened for exclusionary factors such as neurological, musculoskeletal, cardiopulmonary, other systemic disorders and selected drug usage. Out of the 24 subjects who participated in the acquisition session only 22 subjects completed the 3 follow-up sessions (F1, F2 and F3) and thus only 17 subjects participated in the last follow-up session (F4). Prior to participation, all subjects gave their informed consent as approved by the Institutional Review Board.

Experimental set-up. Two sliding devices were placed side-by-side. Each was capable of inducing a slip with a low-friction, non-motorized moveable top plate (65 x 30 cm, 2.7 kg) mounted on a frame with linear bearings of 1.2 m long, which was then bolted onto two force platforms (OR6-5-1000, AMTI, Newton, MA). These devices were locked and embedded in a seven-meter walkway and hidden by the stationary decoy platforms surrounding it. The actual coefficient of friction obtained from ground reaction forces (GRF) measurements was less than 0.05. The two top plates were offset by 9.0 ± 5.0 cm from each other to induce dual slips. Such an offset was based on previous findings on the landing
positions of the protective step, relative to the slipping limb at self-selected regular speeds, and fine tuned based on the height and step lengths of the subject (Bhatt et al. 2005a).

The slips were induced by a computer controlled release mechanism that unlocked one of the moveable platforms at the beginning of each trial without the knowledge of the subject. The second plate was released upon touchdown of the trailing limb when the pre-set loading threshold was exceeded. Once released, the moveable platforms were free to slide on the linear bearings permissible up to a maximum travel distance of 150 cm for right and 100 cm for left before locking into the end position. A computer program written in LabView (National Instruments Inc., Austin, TX) was used for online monitoring of GRF and generation of the lock-release signal. The subjects wore their own athletic shoes and a full-body safety harness, which was attached at the shoulders by a pair of shock absorbing dynamic ropes to a manually-driven trolley on a ceiling-mounted I-beam. The rope lengths were adjusted so that the knees could not touch the surface of the floor upon suspension.

**Acquisition session.** In the acquisition session, the subjects were told that they would walk for a block of trials at their preferred regular speed, and that they “may or may not be slipped”. They were also told that in case they slipped, they should try to recover their balance and continue walking. At the beginning of the experiment, the subjects performed 10 regular walking trials at their self-selected speed. The experimenter would then intentionally adjust each subject’s starting position so that his or her future slipping (right) foot would land entirely on the moveable plate at touchdown. All subjects were able to take at least three steps before stepping on the moveable platform. On the 11th trial, a slip was induced, without prior warning or practice. The subjects were not aware of which trial, or where on the walkway the slip would occur. After exposure to the 1st unexpected slip, the subjects were told to continue walking at the same speed as that of the previous trial and that they “may or may not” be exposed to a slip again. The training paradigm had 37 trials, consisting of a block of 8 repeated slips (S1-8), a block of 3 non-slips (NS1-3), another block of 8 slips (S9-16), followed by the second block of 3 non-slip trials (NS4-6) and a final block of 15 mixed trials (Figure 1). The randomly selected sequence of the mix block was consistent for each subject: S17-18, NS7-8, S19, NS9, S20, NS10, S21-22, NS11-12, S23,
NS13, and S24 (Figure 1). Although previous studies have established that 3-5 repeated slips are sufficient for adaptive improvements in balance loss (Bhatt et al. 2005b; Pavol and Pai 2002), the “overlearning” with the extra trials, consisting of a combination of blocked and random practice was designed to further enhance retention (Schmidt and Lee 1999).

**Follow-up sessions.** The single acquisition session was followed by 4 follow-up sessions (F1 through F4) conducted at intervals around 1 week, 2 weeks, 1 month, and 4 months. The accuracy of the intervals was within a deviation of 1 or 2 days in the first two follow-up sessions and within a deviation of 3 to 5 days in the latter two follow-up sessions. For each follow-up session the setup and instructions were identical to the acquisition session with one exception. That is, only one unexpected slip was always induced last after the subjects had walked a randomly selected number of regular (natural) walking trials, anywhere from a minimum of 8 to a maximum of 13. Thus, there was only one slip trial, which constituted any trial number ranging from 9 to 14 depending on the number of preceding regular walking trials. This random number of regular walking trials was adopted to prevent subjects from predicting the trial when a slip would occur.

**Data collection and reduction.** Twenty-four full body light reflective markers were attached to the subjects’ torso and bilateral upper and lower extremities, while one marker was attached to each moveable platform. Marker coordinates were recorded at 120 Hz using a 6-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA). Marker displacement data was low-pass filtered at marker-specific optimal cut-off frequencies (range: 4.5-9 Hz) using a recursive second-order Butterworth Filter (Winter 2005). Force plate, harness load cell data, and trigger-release onset signal were collected at 600 Hz using a 64 channel, 16-bit A/D converter. The ground reaction force and motion data were time synchronized at the time of data collection.

**Analysis of gait stability.** The COM position and its velocity were calculated from the kinematic data using known gender-dependent segmental parameter information in a 13-
segment representation of the body (de Leva 1996). The position of the COM in the anteroposterior direction was expressed relative to the rear of the BOS (X_{COM/BOS}) of the most recent foot to touchdown (i.e., the heel of the sliding foot for slip onset) and normalized to foot length. The COM velocity in the anteroposterior direction was expressed relative to the velocity of the BOS (X_{COM/BOS}) and normalized as a dimensionless fraction of $\sqrt{g \times h}$ (McMahon 1984), where $g$ is the acceleration due to gravity, and $h$ is the height of the subject.

Stability was assessed through comparison of the COM state (i.e., its position and velocity) with the previously published threshold values for backward balance loss under slip conditions (Pai and Iqbal 1999). Stability was defined as the shortest distance from this predicted boundary for backward balance loss to the instantaneous COM state (Bhatt et al. 2005a; Pai et al. 2003). The model simulation predicts that a backward loss of balance must occur for COM states below the threshold (i.e., stability < 0). Backward balance loss should not occur when the stability measure is above the predicted value for backward balance loss (i.e., stability > 0). Thus, more positive values indicate greater stability against backward balance loss. Conversely, a COM state further below the threshold represents an increased likelihood of backward loss of balance under slipping conditions (Bhatt et al. 2005a; Pai et al. 2003).

Pre-, post-slip adjustments and outcomes. Analyses were restricted to the anteroposterior direction and included the last three regular walking trials preceding the first slip and all the following trials. The instances of step liftoff and touchdown were identified from the vertical ground reaction forces. These values were identified from foot kinematic data if the touchdown occurred outside of the force plates or if both feet were on the same force plate at an instance. Pre-slip stability was measured and noted at touchdown of the slipping limb. Post-slip stability was recorded at liftoff of the contralateral limb. To further understand the contributing factors for adaptive changes in the COM stability based on the findings from the previous studies, (Bhatt and Pai 2005; Bhatt et al. 2005b) we analyzed the changes in the X_{COM/BOS} at pre-slip touchdown of the slipping limb and the BOS velocity.
\( X_{\text{BOS}} \). The latter was obtained from the heel marker of the slipping limb at post-slip liftoff of the contralateral limb. To examine differences in gait speed between sessions, we also analyzed \( X_{\text{COM/BOS}} \) at pre-slip touchdown of the slipping limb.

When the contralateral limb landed posterior to the sliding heel with negative values in post-slip step length during the slip, the trials were classified as loss of balance trials with protective stepping. Conversely, trials with the contralateral limb landing anterior to the sliding heel and positive post-slip step length were classified as “no loss of balance” trials, in which protective stepping was not needed and forward progression was not disrupted.

**Statistics.** Trial-to-trial changes in pre- and post-slip onset stability of the acquisition session were examined using one-way ANOVA for repeated measures. The following selected trials were included in these analyses: S1, S5, and S8 of the first slipping block, S9 and S16 of the second slipping block, and S17 and S24 of the mixed block. In addition to the conventional choice of the first and the last trial of each slipping block, the 5th trial of the first slipping block was included in the analysis similar to previous studies (Bhatt et al. 2005b; Pavol and Pai 2002). The main effects of these analyses were followed up with planned comparisons between consecutive trials and between S1 and S24 using paired t-tests. Furthermore, the outcome for each subject on each trial was determined and categorized as either balance loss (value = 0) or no balance loss (value = 1). Trial-to-trial changes in incidence of balance loss were examined using Cochran’s Q test and post hoc Wilcoxon Signed Ranks tests. Only the 22 subjects who had a complete data set were included in this part of the analyses.

The S1 and S24 of the acquisition session and all 4 slips obtained from each of the 4 sessions from F1 to F4 were included in the retention analysis. Two, one-way ANOVAs for repeated measures were performed with pre- and post-slip stability as the dependent variables and the slip trials (S1 and S24, and F1 through F4) as the repeated factor (session). The main effects of the ANOVA were followed with planned t-tests between consecutive trials included in the analysis and between S1 and S24 and each of the 4 follow-up slip trials, respectively. The
existing last slip trial of the mixed block (S20) was used to substitute that of the missing last trial of the same block (S24) in two subjects. Similar analyses were also performed on pre-slip $X_{\text{COM/BOS}}$ and post-slip $\dot{X}_{\text{BOS}}$. The Cochran’s Q test with post hoc Wilcoxon Signed Ranks tests were performed to test changes in incidence of balance loss across these slip trials.

Post hoc analysis was conducted to evaluate individual subjects' retention of the acquired behavior. The subjects were divided into three logical subgroups depending on their outcome in all follow-up sessions available for analysis: “good” (no balance loss in every session), “poor” (balance loss in every session), and moderate (the rest between these two extremes). A two-way ANOVA for repeated measures was conducted on post-slip stability with ‘group’ as the independent factor and ‘session’ as the repeated factor (S1 and S24, and 3 slips derived from F1, F2, and F3). Significant main effects and interactions were resolved by conducting three planned one-way repeated measures ANOVAs on each group with follow-up planned t-tests between consecutive trials. Since 5 individual subjects failed to return for the last follow-up session, separate paired t-tests were used to estimate the changes occurring between F3 to F4. A post hoc linear regression analysis was performed to correlate the percentage of balance losses on the acquisition session with that of all the follow-up sessions combined.

A significance level of 0.05 was used for all the analyses, although absolute p values between 0.05 and 0.001 for significant t-test comparisons were reported. Analyses were performed using SPSS (Chicago, IL).

Results

Acquisition. There was a main effect of trial for both pre- $[F(6, 126) = 14.33, p < 0.001]$ and post-slip stability $[F(6,126) = 47.33, p < 0.001]$. As in Figure 2a, with repeated slip exposure, subjects showed a significant increase in pre-slip stability by S5 compared to the first unexpected slip in S1, with no further increase in that block ($p > 0.10$ between S5 and...
Subjects demonstrated significantly lower stability during the first re-slip exposure in S9 than in S8 of the previous block \((p = 0.002)\). By the next slip in S10, pre-slip stability improved and was maintained for the remaining slip block. The pre-slip stability did not improve further in the final mixed block \((p > 0.10\) between S16 and S17, and between S17 and S24).

Trial-to-trial changes in post-slip stability were similar to changes in pre-slip stability during the first block of repeated slip exposure, showing a significant increase in post-slip stability from S1 to S5 \((p < 0.001)\) and no change between S5 and S8 \((p > 0.10)\) (Figure 2b). However, post-slip stability on the first slip in S1 was much lower compared to the preceding regular walking trial. In the 1st slip of the second block of slips (S9), post-slip stability was lower compared to the last slip of the first block (S8) \((p = 0.02)\). Yet, it improved in S10 and this increase was similarly maintained for the remaining slips of the block. Post-slip stability remained at a steady state for all the slip trials thereafter \((p > 0.10\) between S16 and S17, and between S17 and S24). In the absence of perturbation, i.e., non-slip (NS) trials, post-slip stability was greater than the slip trials and even greater than the natural walking trials preceding the first slip (Figure 2b).

The improvements in stability made before and after the onset of perturbation were followed by a corresponding decrease in incidence of balance loss. In S1, all subjects exhibited a loss of balance. This incidence however, decreased with repeated slip exposure \([Q (6, 22) = 86.79, p < 0.001]\) (Figure 3). The incidence of balance loss reduced to the 8% level by S5 \((p < 0.001)\) and remained at that level till S8 \((p > 0.10\) between S5 and S8). Upon S9 after three non-slip trials, the percentage of balance loss increased from 8% to 29% \((p = 0.05)\). However, it rapidly reduced in S10 and was maintained at around the 4% level by S16 \((p < 0.05)\). Following another block of 3 non-slip trials, the incidence of balance loss was around the 4% level in S17 \((p > 0.05\) between S16 and S17), and reduced to zero in 4 of the last 5 slip exposures (Figure 3).

**Retention.** There was a significant main effect of session on pre-slip stability \([F (5, 30) = 10.00, p < 0.001]\) and post-slip stability \([F (5, 30) = 32.73, p < 0.001]\). Pre-slip stability was
significantly greater in F1 than in S1 (p < 0.001), but not different in F1 from that in S24 (p > 0.10), nor was it different from that in F2, F3, and F4 (p > 0.10 for all consecutive comparisons conducted, Figure 4a). Post-slip stability was significantly greater in F1 than in S1 (p < 0.001), yet significantly lower in F1 than that in S24 (p < 0.02), with no further change in F2, F3, and F4 (p > 0.10, Figure 4a).

Subjects were able to retain the reduction in balance loss incidence \( [Q(5, 17) = 38.70, p < 0.001] \) around the 40% level in each follow-up session as compared to the 100% incidence in the first slip of the acquisition session (p < 0.001 for all comparisons) (Figure 4b). The 40% level, however, was much lower than the no balance loss in S24 as well as the 4% level in S17 (p < 0.005). No significant difference in incidence of balance loss was found between the consecutive follow-up sessions (p > 0.10) (Figure 4b).

The changes in pre-slip stability were accounted for by changes in \( X_{\text{COM/BOS}} \) [\( F(5, 80) = 8.8, p < 0.001 \)] (Figure 5a). There was a significant anterior shift in \( X_{\text{COM/BOS}} \) from S1, to S24 of the acquisition session (p < 0.001). The \( X_{\text{COM/BOS}} \) was maintained at that level for the first follow-up session (p > 0.10), as well as for the remaining follow-up sessions (no significant change in \( X_{\text{COM/BOS}} \) between the consecutive follow-up sessions, p > 0.10). There was no significant change in gait speed at pre-slip touchdown of the slipping foot (\( \dot{X}_{\text{COM/BOS}} \)) between sessions [\( F(5, 80) = 0.98, p > 0.10 \)]. The changes in post-slip stability were accounted for by changes in \( X_{\text{BOS}} \) [\( F(5, 80) = 26.56, P < 0.001 \)]. There was a significant decrease in \( X_{\text{BOS}} \) from S1 to S24 (p < 0.001), however, this decrease was not maintained on the first follow-up session which showed a significant increase in \( \dot{X}_{\text{BOS}} \) compared to S24 (p < 0.005). There was no further change in \( \dot{X}_{\text{BOS}} \) between the consecutive follow-up sessions (p > 0.10 for all paired planned comparisons between consecutive sessions) (Figure 5b).

**Individual differences.** Post hoc analysis between the three subgroups, depending on retention frequency on the follow-up sessions, showed a significant main effect of session [\( F(4, 76) = 31.04, p < 0.001 \)] and a trend for group effect [\( F(2, 19) = 2.25, p = 0.13 \)], with no group x session interaction [\( F(8, 76) = 1.16, p > 0.10 \)]. The group with “good” retention (n = 8) had a significantly greater stability on the follow-up sessions as compared to S1 [main
effect of session: F (4, 28) = 21.00, p < 0.001], and no difference in their post-slip stability as compared to S24 (p > 0.05, Figure 6a). Conversely, the group with “poor” retention (n = 3) had no difference in stability on follow-up sessions (F1, F2, and F3) compared to S1 (p > 0.10 for all comparisons). They also had much worse post-slip stability on the follow-up sessions than in S24 (p < 0.05 for F1, F2 and F3, and p = 0.12 for F4 Figure 6a), resulting in an inability to prevent balance loss incidence on the follow-up sessions (Figure 6b). Further post hoc analysis indicated that the “poor” retention group had a less “flat foot” with a greater foot angle and a greater post-slip BOS velocity on F1 compared to S24 (Foot angle: 11.0 ± 4.0° on S24 vs 14.95 ± 4.97° on F1, p = 0.07; BOS velocity: 0.3 ± 0.13 m/s on S24 vs 0.7 ± 0.11 m/s on F1, p = 0.05), contributing towards lower post-slip stability. The group who had various degrees of retention (n = 11) had significantly greater post-slip stability on the follow-up sessions than that in S1 [main effect of session: F (4, 40) = 22.60, p < 0.001; p < 0.001 for all comparisons]. A slightly lower post-slip stability was found for this group during the follow-up sessions compared to the last slip in acquisition session (between S24 and F1, p = 0.07; and F2, p = 0.05; and F3, p = 0.05, Figure 6a), associated with a wide range of balance recovery outcomes (Figure 6b).

There appears to be individual differences in the loss of balance during the acquisition session. Fourteen of the 22 subjects rapidly acquired this ability and lost their balance only once or twice in 24 slips during acquisition (Figure 6c). None of the subjects in the “good” retention group experienced more than 2 balance losses during the 24 slip trials, compared to that experienced by 7 subjects (63%) in the moderate retention group and 1 subject (33%) in the “poor” retention group. Regression analysis confirmed a significantly positive relationship between the percentage of balance losses on the acquisition session (over all 24 trials) and the percentage of balance losses over all the available follow-up sessions (y = 2.2857x + 11.564, R² = 0.37, p < 0.01, Figure 6d).
Discussion

Our results indicated the plasticity of the CNS, which is capable of rapidly acquiring a stable COM state under unpredictable slip conditions and retaining such improvements for months, resulting in a reduced likelihood of balance loss. Subjects were able to show significant retention of pre- and post-slip gait stability for at least 4 months after the initial acquisition session. The retained improvement in these variables was lower, however, compared to that acquired at the end of the acquisition session. Similarly, incidence of balance loss on each of the follow-up sessions was around the 40% level compared to 100% and nearly 0%, respectively at the beginning and end of the acquisition session. Our study revealed that the less-than-perfect retention resulted, to some extent, from individual variability rather than across-the-board generalized behavior.

Acquisition Session. As hypothesized, subjects were able to rapidly improve the pre- and post-slip stability, leading to a rapid decrease in incidence of balance loss. After they experienced mixed blocks of trials of slips and non-slips, a steady state was reached for the COM stability and likewise a low incidence of balance loss (Figure 2 and 3). This COM state would be desirable, because it would be stable regardless of whether a slip occurs as previously demonstrated theoretically and empirically (Pai et al. 2003; Pai and Iqbal 1999). Under an elevated threat that the surface may be slippery, by adopting a steady-state movement trajectory that is stable and simultaneously satisfies different friction coefficients, a person can reduce his or her reliance on prompt and precise knowledge with respect to slippery surfaces. Such movement strategy which incorporates the control ability to neutralize the perturbation, would enable one to maintain stability regardless of whether a slip occurs or not, hence reducing reliance on the reactive recovery response. One may not, however, be able to obtain the desired steady-state movement trajectory to protect against a fall by merely knowing that a slip may occur. Recent evidence has shown that only awareness of upcoming slippery surfaces versus actually experiencing the slip, yields different adaptations (Heiden et al. 2004), with the latter being more beneficial for prevention of balance loss and falls (Bhatt et al. 2005b). The fact that all young adults tested while walking at their preferred speeds[,] experienced backward loss of balance during the 1st slip
exposure, (Bhatt and Pai 2005; Bhatt et al. 2005b) indicates that the desired movement
strategy is not inherent and must be acquired through motor training even among healthy
individuals. Due to its ecological implication, such stability training would be warranted,
especially among those individuals with an elevated risk of falls.

This paradigm of “slip--non-slip--re-slip” employed in the acquisition session has extended
our previous findings on adaptation to forward slips during gait (Bhatt et al. 2005b). The
present results indicate that the adaptation effects acquired in the first block of slips may
show an immediate waning effect when the perturbation stops. Such a waning effect may
strongly depend on the context which the CNS is anticipating to experience (Bhatt et al.
2005b; Vetter and Wolpert 2000). Upon re-exposure to the perturbation in the same session,
the CNS appears to be capable of rapidly modifying its internal representation of stability
limits until this practice reaches a steady state. During this process, the CNS may have
shifted from relying on context prediction for an upcoming situation to pre-programming a
desirable COM-state trajectory, which would be stable under a variety of environmental
contexts.

RetentionPolicy. Our results supported the second hypothesis that subjects showed a
significantly greater pre- and post-slip stability on all the follow-up sessions compared to the
first slip of the acquisition session. Contrary to our next hypothesis, however, subjects only
exhibited complete retention in pre-slip stability, but the average post-slip stability was
considerably lower in the follow-up sessions compared to the last slip of the acquisition
session. Similarly, the incidence of balance loss was significantly lower than the first
exposure of the acquisition session (100% compared to ~ 40%, Figure 4b), but was higher
than the last exposure of the acquisition session. Our results confirmed previous findings
which indicated that subjects were able to completely retain adaptive improvements in pre-
slip stability up to a period of 12 months or longer when tested under the same environment
(Bhatt and Pai 2005). However, our findings revealed that when the intensity of a single
training is sufficient and a re-test is done at shorter intervals than 12 months, post-slip
stability is also retained.
Our analysis indicates that inter-subject variability could be an important factor in affecting post acquisition retention. Post hoc analyses were able to identify subgroups of individuals with various abilities to retain what has been acquired. One subgroup of 8 subjects had little or no failure during the 4-month period, indicating that it is possible to completely retain improvement in post-slip stability with no balance loss in the follow-up sessions. Conversely, another subgroup of 3 subjects, completely failed to retain the training effect during the 4-month period. The remaining 11 subjects fit into a spectrum somewhere in-between. The post hoc analysis enabled us to detect such individuality in adaptation and retention related to stability against slip-related backward balance loss in walking, which might not have been revealed if only the group mean was used to detect the changes.

We have further investigated other identifiable factors, within the realms of this study, which could possibly have explained the individual differences. We could find no significant differences in anthropometric variables such as subject weight and height or cognitive status, which could account for the difference in learning. Also, there were no apparent differences in activity level from sedentary to athletic in these individuals at the time of recruitment. Subjects were recruited from the University pool of students matching the inclusion criteria and thus consisted of a homogeneous population. The possible differences in cognitive factors such as personality (e.g., more risk taking or more cautious), level of motivation (e.g., not bothered by being sloppy or clumsy), or expectancy of slip (i.e., error in predicting an impending slip) may have played a role in the retention of acquired performance. Nevertheless, these attributes would be difficult to quantify and have not been included in the study. Our post hoc analysis did indicate that on the first follow-up session, subjects in the “poor” learners group had less tendency of “flat foot” landing compared to their last acquisition slip. This difference could have led to a higher slip velocity and thus lower post-slip stability (Bhatt et al., 2005b).

The intensity of training could also have played a role, affecting the variability in post-slip stability. This paradigm may have provided sufficient stimuli to train one subgroup of 8 subjects for complete retention of the training effect. Yet, the same stimuli might not be enough to produce prominent learning effects in other subjects exhibiting mediocre or “poor”
retention (63% of subjects in the moderate group and 33% of subjects in the “poor” retention
group required more acquisition trials to prevent loss of balance). These subjects might have
benefited from more repetitions or acquisition sessions. It is noteworthy that those subjects
who did not do well during retention, tended to take more repetitions to prevent balance loss
in the acquisition session (account for about 37% of variability between incidence of balance
loss between acquisition and follow-up sessions, Figure 6). Our data showed that individuals
who did well in the initial acquisition session were inclined to perform better in the follow-up
sessions and vise versa. There might be two types of deficiencies causing poor retention.
One type with an origin in adaptation as predicted by the correlation, and the other in
remembering what has been adapted (i.e., in retention). Indeed, two of the three ‘poor’
learners adapted well and would belong to the latter group. The importance of “over
learning” for retention may benefit both types and is well recognized in the form of repetition
with blocked or random practice and multiple sessions (Hart et al. 1997; Lemoine et al. 1993;
Markowitsch et al. 1985). Rapid adaptation, which was achieved in a few repetitions with
the latter type, may not necessarily yield sustainable long-term learning effects. Therefore, it
is possible that greater intensity and training frequency can improve these few individuals’
retention. Both the small sample size in each of the subgroups and the design of the study
limit the generality of our findings.

The increases in pre-slip stability are achieved, arguably, through feedforward control,
causing an anterior shift in COM position with shortening of pre-slip step length (Bhatt et al.
2005b). Similarly, our results indicated that changes in pre-slip stability were primarily
accounted for by an anterior shift in the COM position relative to the BOS with no significant
changes in the COM velocity and gait speed (Bhatt et al. 2005b). This could have resulted
from the imposed instructional constraints on the subjects, to continue walking at the initial
speed after the first slip, during the acquisition session and to walk at their natural self-
selected speed on the follow-up sessions. In contrast, increases were seen in both COM
position and its velocity to repeated slips during sit-to-stand (Pavol and Pai 2002), despite the
instruction given to the subjects to rise “as fast as possible” both prior to and post first slip.
In addition to other likely contributors, the differences in task objectives and in posture and
segment motion state could have accounted for these differences in adaptive control during these two tasks.

Following repeated slips, adaptive improvements in post-slip stability could possibly occur due to a shift from reliance on sensory feedback for balance control to a feedforward influenced, reactive control that regulates BOS perturbation intensity. For example, adaptive reductions in pre-slip foot angle with repeated slip exposure have been shown to correlate with reductions in braking impulse under the slipping limb during double stance. This in turn strongly correlates with reductions in BOS velocity of the slipping limb heel (Bhatt and Pai 2005; Bhatt et al. 2005b). Similarly, our results indicate that increases in post-slip stability from the 1st slip to the last slip of the acquisition trial were achieved by significant reductions in BOS velocity. Also, the reduction in post-slip stability on the follow-up session correlated strongly with reductions in BOS velocity. Notably, in absence of a perturbation during the NS trials, the COM state at liftoff was still more stable against slip-related backward balance loss than natural walking prior to the 1st slip exposure. Taken together, these findings further support the postulation of strong feedforward influence on post-slip stability proposed in previous studies (Bhatt et al. 2005b).

The decreased performance in post-slip stability on the follow-up sessions may also be affected by subjects’ inability to retain the minimal feedback based reactive control, still needed post-slip, to control the BOS perturbation intensity once perturbation onset occurs (Bhatt et al. 2005b). A recent study has shown that subjects were unable to retain the acquired adaptation in feedback-based reactive postural response (Schwabe et al. 2004). Another study has shown that subjects were able to retain the training-induced reduction in postural sway, mediated by some level of conscious control and feedforward mechanisms, for up to 30 days (Tjernstrom et al. 2002). Such evidence suggests that adaptation in feedback control mediated by reflex responses may not be transformed into permanent representations similar to that of triggered responses or motor programs within the nervous system.
The neurophysiological mechanisms underlying retention for acquired posture and gait adaptation are less studied and not well understood. It is proposed that the CNS acquires new sensory-motor relationships or strategies through the process of adaptation to enhance stability to cope with changes in external constraints and prevent incidence of balance loss and falls. Such a process, associated with building or updating internal representation of one’s stability limits (Bhatt et al. 2005b; Pai et al. 2003), is probably associated with the shift from reliance on long-loop reflex pathways within the brain stem and the spinal cord (Forssberg et al. 1975; Hiebert et al. 1994) to increased subcortical and cortical influence (Drew et al. 2002). Such a shift would also result in developing an enhanced memory from the short-term labile state to a longer lasting stable state through the process of consolidation (Kandel et al. 2000; McGaugh 2000; Shadmehr and Holcomb 1997; Shadmehr and Brashers-Krug 1997). This process of reorganization of brain representation, involves structural changes within the CNS such as gene expression, new protein synthesis and enhancing synaptic connections and connectivity and usually occurs in higher centers (Kandel 2001; Shadmehr and Brashers-Krug 1997). A memory becomes increasingly “resistant to interference from other competing and disrupting factors with the passage of time” during consolidation (Walker et al. 2003). Evidence suggests that retention of newly acquired or enhanced sensori-motor relationships involving higher control systems and conscious control and feedforward mechanisms could be easily consolidated and stored (Tjernstrom et al. 2002). This contrasts with sensori-motor relationships involving or relying solely on the subcortical locomotor-balance centers (pons medulla) and long-loop reflex systems (Schwabe et al. 2004). The fact that subjects in this study were able to show retention in post-slip stability further strengthens our proposition of shifts with increasing influence of feedforward control in reactive response during adaptation in the acquisition session. In the present study, we have increased the intensity of training in the acquisition session to such an extent that it could have further strengthened the influence of feedforward control, resulting in an improved overall retention as compared to our previous attempt, relying on only 5 repeated exposures to slip (Bhatt and Pai 2005). Subjects’ regular walking can be different from their training-acquired gait pattern that is desirable under heightened threat of encountering slippery surfaces. Regular gait pattern is
re-enforced on a daily basis, and may interfere with the consolidation processes, leading to
decay in motor memory of the acquired protective gait pattern. This could probably explain
poor performance in some subjects on the follow-up sessions. Each time the memory is
reactivated, it is probably in a fragile state, susceptible to interference and needs to be “re-
consolidated” (Nader et al. 2000; Walker et al. 2003). The slip on each follow-up session
may have served as a “memory refresher” to induce further consolidation (Milekic and
Alberini 2002), explaining why some subjects might have experienced a balance loss on the
first follow-up session but not on the subsequent one. Conversely, subjects may not have
been able to re-consolidate this memory, showing poor performance in a subsequent follow-
up session. This could explain the random frequency of balance loss between subjects and
sessions (Figure 6b). The relatively complete retention within feedforward control in pre-slip
stability could have involved the explicit or episodic learning associated with spatial memory
which could have encoded the lab environment and possibility of slips (Frank et al. 2004).
When brought under the same environment, subjects could have recalled and retrieved the
event experienced and interacted with the procedural system to be appropriately activated
(McClelland 1994; Micheau et al. 2004). Yet, episodic learning and improved knowledge of
the slip were apparently not sufficient for keeping some from falling backwards. Failure in
proper interaction with the procedural system or inappropriate activation could account for
failures in retention associated with post-slip stability. While we were able to identify a
subgroup of healthy young adults, who had exhibited little if any motor memory
deterioration, such a trait was clearly detectable amongst individuals in the “moderate” and
“poor” retention categories. Our results reflect that these few individuals probably had more
problems in long-term memory compared to the immediate near-term memory, since they
were all able to adapt but not able to have “good” retention. Also, the role individual
cognitive capacity plays in retaining slip stability, needs further attention, particularly in the
older population. Nevertheless, our study demonstrates a general trend of “good” motor
learners with good adaptation and retention skills and another subgroup of individuals
(mediocre to poor motor learners) who eventually adapted well (some with difficulty) but
failed to retain the acquired skills, possibly due to a motor memory decay.
Our current study has demonstrated the feasibility of successful longer-term retention after exposing subjects to sufficient stability training to prevent backward balance loss. Without any explicit instruction, nearly half of the healthy young subjects were able to quickly establish desirable movement strategies to prevent incidence of balance loss and to retain such motor memory on all the follow-up sessions. The current study altered both the number of repetitions and the interval to the follow-up session(s) from the previous study (Bhatt and Pai 2005). Therefore, it did not allow us to determine if either a single enhanced acquisition session with more training trials or a shorter retention interval alone, or both combined were responsible for the positive retention effects. It is likely that each follow-up session might not have yielded additional, cumulative training effect, because there was no session-to-session improvement in stability or in outcome. It is nevertheless possible, that the single slip exposure on each of the follow-up sessions serves to prime the motor memory for the subsequent session (Schacter and Buckner 1998; Schacter et al. 1993; Tulving and Schacter 1990), and this could have prevented overall deterioration in performance in the 4-month period. Our previous results support this notion of “priming” where all subjects lost their balance in the first unexpected slip after 12 months or longer, but it was perhaps sufficient to facilitate a rapid re-acquisition, resulting in a significantly lower incidence on balance loss on the 2nd slip (Bhatt and Pai 2005).

In summary, the present study revealed that gait stability improvements acquired with an intensive single acquisition session, consisting of multiple blocks of slips, can be sufficiently retained for a period of 7 days up to 4 months, to alter the outcome of balance control when exposed to an unexpected slip. This study has also revealed a correlative relationship between acquisition and retention, such that the performance during the acquisition phase might be predictive of future risk for backward balance loss. Lastly, future studies may need to assess the extent to which such training effects can be reproduced among older adults, in whom slip-related falls, preceded by backward balance losses, can cause serious consequences.
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References


Figure Legends

Figure 1. Experimental design for the repeated ‘slip—no-slip—re-slip’ paradigm, consisting of two blocks of slips, S1-S8, S9-S16, a mixed block interspersed with additional 8 slip and 7 non-slip trials, and the non-slip blocks in between. These 37 trials followed 10 “natural” walking trials at one’s preferred speed. Subjects were entirely unaware of trial conditions and were given neither practice trials nor instructions other than a slip “may or may not occur”.

Figure 2. Group means of a) pre- and b) post-slip-onset stability during the acquisition session. Nat = unperturbed, self-selected “natural” walking trials preceding the first slip, NS = a block of 3 non-slip trials following a block of slip trials. Data points with standard deviation bars are the trials included in statistical analysis. More positive values indicate greater stability. The center of mass state (its position and velocity) are both in dimensionless units. Thus, the stability measure is also a dimensionless variable. Significant differences with respect to the preceding trial included in the statistical analysis are indicated, *, p < 0.05. The sample size was 24 for trials all natural trials, S1-S5, NS1-3, S9-13, NS4-6, and the first 9 trials of the mixed block, and n = 22 for the remaining trials.

Figure 3. Histogram displaying incidence of backward balance loss (in percentage) for the acquisition session. Nat = walking trials at self-selected “natural” speed, NS = non-slip trials where the moveable/slipping plate was in a locked position (open bars). The acquisition session included two slipping blocks S1-S8 and S9-S16. The Mixed block consisted of interspersed slip and non-slip trials. LOB = loss of balance (solid bars), NLOB = No loss of balance (patterned bars). Significant differences with respect to the preceding trial included in the statistical analysis are indicated: ***, p < 0.001; **, p < 0.05; *, p = 0.05. n = 24 for trials all natural trials, S1-S5, S9-13, and the first 4 slip trials of the mixed block; n = 22 for the remaining trials.

Figure 4. (a) Changes in pre- and post-slip stability (means ± SD), and (b) incidence of balance loss in percentage (%), on the first and last slip trials of the acquisition session (S1
and S24 respectively) and the slip trial on each of the follow-up sessions conducted 7 (F1),
15 (F2), 30 (F3) and 160 (F4) days after the acquisition session. More positive values
indicate greater stability. n = 22 for all trials except for F4 where n = 17. Significant
differences with respect to the preceding trial included in the statistical analysis are indicated:
***, p < 0.001; *, p < 0.05.

Figure 5. Group means ± SD of (a) pre-slip COM relative to BOS (X_{COM/BOS}) normalized to
foot length and (b) BOS velocity (\dot{X}_{BOS}) for the first and last slip trials of the acquisition
session (S1 and S24 respectively) and the slip trials on the 4 follow-up sessions (F1, F2, F3
and F4). ***, p < 0.001; *, p < 0.05.

Figure 6. (a) Group means (& SD) of post-slip stability in each subgroup (poor, moderate
and good) for the first and last slip trials of the acquisition session (S1 and S24 respectively)
and the slip trials on the 4 follow-up sessions (F1, F2, F3 and F4). More positive values
indicate greater stability. (b) Frequency histogram showing the history of incidence of
balance loss for each subject over each of the 4 follow-up sessions. Subjects are ranked
depending on the performance group in an ascending order from “good” (n = 8) with no
balance loss to “poor” retention (n = 3) who lost balance in every recorded session. Notice 5
subjects did not return for the 4th session. (c) Frequency histogram displaying the number of
balance losses experienced by the same subjects as in (b) during the acquisition session.
Note the subject number corresponds to that in Figure 5b. (d) Regression analysis correlating
the percentage of balance losses for each subject on the 24 slips of the acquisition session
with that of all the available follow-up sessions (F1 through F4). Each data point represents
an individual subject. Note, n = 22 but several data points overlap and only 14 are visible.
***, p < 0.001; ** p < 0.05; * 0.05 < p < 0.10.
Figures

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Figure 1

![Graph showing pre-slip stability with data points and error bars for different conditions.]

Figure 2

![Graph showing post-slip stability with data points and error bars for different conditions.]

Figure 3
Trials

Incidence of Balance loss (%)

LOB
NLOB

Nat NS NS Mixed Block S24

Figure 3
Figure 43

a) Pre-slip Stability

b) Incidence of Balance Loss (%)
Figure 5
Trials S1 S24 F1 F2 F3 F4
Post-slip Stability

-0.6
-0.4
-0.2
0.0
0.2
0.4

Good

***
***
***
***
***

Moderate

Poor

123456789 10 11 12 13 14 15 16 17 18 19 20 21 22
# of LOB in Follow-up sessions

F1 F2 F3 F4

No loss of balance
Loss of Balance (LOB)

123456789 10 11 12 13 14 15 16 17 18 19 20 21 22
Subject Number

# of LOB for Follow-up (%)

y = 2.2857x + 11.564
R² = 0.3684

Figure 6