Long-term Retention of Gait Stability Improvements

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Running title: Gait stability retention and backward balance loss

Keywords: Fall prevention, feedforward control, adaptation, balance control, motor memory

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Abstract

Evidence of long-term modification of behavior - in particular, gait alterations in response to repeated exposure to slips - within the locomotor-balance control system is limited. The purpose of this study was to examine whether improvements in fall-resisting behavior, as reflected by improvements in gait stability could be retained on a long-term basis. Eight healthy young subjects were exposed to a block of repeated slip trials during a single acquisition session consisting of five repeated slip exposures; the same subjects were then re-tested using the same protocol at a minimum of 12 months later. Pre- and post-slip gait stability for all slip trials was measured at touchdown (slipping limb) and liftoff (contralateral limb) based on the center of mass state (i.e., its instantaneous position and velocity) relative to the base of support (BOS) and the predicted thresholds for backward loss of balance. In the acquisition session, subjects were able to increase pre- and post-slip stability, which significantly correlated with a decrease in the incidence of balance loss from 100% (1st slip) to 0% (5th slip). All subjects exhibited a similar balance loss on the 1st slip of the follow-up session. Nonetheless, subjects were able to retain the acquired pre-slip stability with feedforward control on the 1st slip, but not the post-slip stability related to the reactive response. Also, the subjects demonstrated a faster re-acquisition, with only one balance loss on the 2nd slip of the follow-up session, as compared to seven balance losses on the acquisition session. Such rapid improvements were achieved by the significantly greater increase in post- compared to pre-slip stability; this increase was for the most part, a consequence of reductions in slip intensity (i.e., the peak BOS velocity). We concluded that a single acquisition session could only produce limited long-term retainable effects within the locomotor-balance control system. It appeared, however, that the CNS was still primed to more rapidly update its internal representation of gait stability during re-acquisition.
Introduction

Falls are the leading cause of injury-related death or hospitalization in older adult populations and a significant contributor to a decrease in quality of life (Baker and Harvey 1985). Learning to increase the ability of the central nervous system (CNS) to employ successful motor adaptation, i.e., strategies to deal with abrupt changing external constraints, could thus be fundamental in preventing falls and maintaining daily function. Although fundamentally different from an actual fall, unintended loss of balance is often a precursor to a fall. A successfully acquired and retained motor behavior that promotes an individual’s own neuromuscular protective mechanisms by improving stability and reducing loss of balance following perturbation is therefore a pre-requisite to the prevention of falls.

The adaptability of the posture and locomotion control system under various perturbation conditions is well established (Andres et al. 1991; Horak and Nashner 1986; Horak et al. 1997; Keshner et al. 1987; McIlroy and Maki 1995; Rand et al. 1998; Reynolds and Bronstein 2003). Only a few studies have established the beneficial effect of such adaptations with respect to any reduction in balance loss or fall incidence (Owings et al. 2001; Pai et al. 2003; Pavol and Pai 2002; Pavol et al. 2002). Recent theoretical and empirical evidence has, however, demonstrated that the adaptive control of one’s dynamic stability can indeed be successful in preventing backward loss of balance and slip-related falls, if one can adjust his/her center of mass (COM) state (i.e., the COM position and its velocity) relative to the base of support (BOS) above the computationally predicted stability threshold level for backward loss of balance (Pai et al. 2003; Pavol and Pai 2002).

Because stability can be expressed as the relationship between the BOS and the COM, the CNS could achieve its central goal of adaptive stability control by adjusting the trunk and hence the COM motion (via anticipatory adjustments or reactive responses) to catch-up with the perturbed BOS. Alternatively, it could increase stability by minimizing the potential BOS perturbation during gait (Lockhart et al. 2003; Marigold and Patla 2002; ...
You et al. 2001; Bhatt et al. 2005a). However, little is known about the extent to which adapted fall-resisting behavior to external disturbances can be retained (Schwabe et al. 2004). Recently, Tjernstrom et al., (Tjernstrom et al. 2002) demonstrated one-month retention of acquired changes in magnitude of body sway to calf vibrations during stance. It is possible that the retention effect in this study could have been the result of an extensive training period consisting of multiple sessions. In contrast, a few studies on applying fear conditioning in mice have shown that a single acquisition session is sufficient for long-term retention of the acquired stimulus-response behavior within the CNS (Kim and Fanselow 1992; Sacchetti et al. 2004). A similar analogy may hold true where a single session of acquisition to deal with a threatening environment may be sufficient to exhibit long-term retention of the acquired motor behavior. Thus, variations in the time period required to acquire and convert these temporary sensori-motor associations into permanent motor programs are evident (Brashers-Krug et al. 1996; Kandel 2001). These differences may reflect the functional significance of the adaptation response, which itself is conditioned by the penalties imposed upon an inappropriate response by the CNS and the increased potential of injury (Adkin et al. 2000; Carpenter et al. 2001).

The purpose of this study was to determine whether gait stability improvements acquired in a single session could be retained by subjects for at least 12 months. Our hypothesis was that if the CNS were able to retain the acquired stability improvement, subjects would, when re-tested after one year under the same environment, exhibit a pre- (at touchdown of the slipping limb) and post-slip (at liftoff of the contralateral limb) stability significantly greater than the first slip exposure but not significantly different from the last exposure of the acquisition session. The retained improvement in pre- and post-slip stability would, we expected, subsequently be reflected in a significantly reduced balance loss incidence on the 1st slip exposure of the follow-up session.
Methods

Subjects. Eight healthy young subjects (28.5±6 years, 3 males and 5 females) out of the 14 subjects who initially participated in the acquisition session completed the study by participating in the follow-up session. Subjects were included in the study after being screened for exclusionary factors such as neurological, musculoskeletal, cardiopulmonary, other systemic disorders, and selected drug usage (e.g. sedatives, anti-anxiety, anti-histamines). Out of the eight, one subject was a newly joined member of the lab at the time of re-test. It was however, determined definitively, that the subject had not been exposed directly or indirectly to any aspects of the paradigm until the re-test, i.e., not allowed to watch the experiment being performed, analyze data, or participate in discussions about the slipping paradigm. The other seven subjects did not visit the lab nor did they have any contact with us until recruited for the re-test. Prior to participation, all subjects gave informed consent as approved by the University of Illinois at Chicago Institutional Review Board.

Experimental set-up and protocol. Slips were induced using a sliding device consisting of a low-friction, non-motorized moveable platform (29 x 40 cm, 3.85 kg) mounted on linear bearings to a support frame. The device was locked and embedded in a seven-meter walkway and was hidden by the stationary decoy platforms surrounding it. The supporting frame of the sliding device was bolted to a force plate (OR6-5-1000, AMTI, Newton, MA) to measure ground reaction forces (GRF). Three additional force plates were placed in such a way that GRF from the steps before and after contact with the moveable platform could be recorded. Slips were induced by a computer controlled release mechanism that unlocked the moveable platform after touchdown of the slipping foot, when the ratio of the horizontal to vertical GRF exceeded a preset threshold, comparable to a low coefficient of friction of 0.02. The trigger-release signal indicated that the pre-set threshold for the coefficient of friction was exceeded within a maximum of 20 ms from touchdown of the slipping foot. A computer program written in LabView (National Instruments Inc., Austin, TX) was used for online monitoring of GRF and generation of lock-release signal. Once released, the moveable platform slid freely on
linear bearings and locked upon reaching a maximum travel distance of 44 cm. The subjects wore their own athletic shoes and a full-body safety harness 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. The details of the setup are also given elsewhere (Bhatt et al. 2005b).

In the acquisition session, the subjects performed 3 blocks of 10 walking trials each at self-selected slow, regular, and fast speeds, with the regular-speed block performed last. The other two speed blocks were performed first, in random order, with no slips induced. At the beginning of the experiment, the subjects were told that they would be walking for three blocks of trials (the number of trials at each speed was not specified) at each of their preferred “slow” and “fast” speeds, and that they might be subjected to slips. They were told to try to recover their balance upon any slip incidence and then to continue walking. The 1st slip was induced without prior warning or practice trials. The subjects were not aware of which trial, which speed, or where on the walkway the slip would occur. On the 11th trial at “regular” speed, a slip was induced. After exposure to the 1st unexpected slip, 4 consecutive repeated slip trials followed. 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 slipping again. Each subject’s starting position was adjusted so that his or her right (slipping) foot would land entirely on the moveable platform. All subjects were able to take at least three steps before stepping on the moveable platform. When called back for the follow-up session at least 12 months later (mean ± SD: 16 ± 4 months), the subjects followed precisely the same protocol as that of the acquisition session. Because slip-related falls are likely to occur during winter in a yearly cycle (Bentley and Haslam 1998; Gao and Abeysekera 2004), it was considered imperative to determine whether the acquired gait pattern would be stable enough to prevent slip-related balance loss over a 12-month period.

Data collection and reduction. Full body kinematics were recorded at 120 Hz using a 6-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA).
Twenty-four light reflective markers were attached to bilateral upper and lower extremities and torso while one marker was attached to the moveable platform. Marker coordinates were low-pass filtered at marker-specific optimal cut-off frequencies (range: 4.5-9 Hz) using a recursive second-order Butterworth Filter. Force plate and harness load cell data and trigger-release onset signals 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.

Analyses were restricted to the anteroposterior direction and included the last unperturbed trial at regular speed and all the slip trials. When the contralateral limb landed posterior to the sliding heel (negative post-slip step length), the trials were classified as loss of balance trials with protective stepping. Conversely, trials with the contralateral limb landing anterior to the sliding heel (positive post-slip step length) were classified as “no loss of balance” trials in which protective stepping was not needed. Trials with false trigger, faulty landings on the moveable platform (3 in 40 trials), missing markers (1 of the 5th slip trials), and a breakdown of the release mechanism (one person’s 4th and 5th trials), in the acquisition session were excluded from the analysis.

Analysis of gait stability. The COM position and its numerically derived derivative (velocity) were computed 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 ($\dot{X}_{COM/BOS}$) and normalized as a dimensionless fraction of $\sqrt{g \times h}$ (McMahon 1984), where $g$ is the acceleration due to gravity, and $h$ is height of the subject.
Stability was assessed through comparison of the COM state with the previously published threshold values for backward balance loss under slip conditions (Pai and Iqbal 1999). Stability is defined as the shortest distance from this predicted boundary for backward balance loss to the instantaneous COM state (Bhatt et al. 2005b; Pai et al. 2003) as shown in Figure 1. 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. 2005b; Pai et al. 2003).

Pre- and post-slip response. The instants 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 prior to mechanical slip onset, i.e., 85 ± 30 ms before displacement onset of the moveable plate. This was comparable to onset of heel displacement on a “slippery surface” after its touchdown (Redfern et al. 2001). Post-slip stability was recorded at liftoff of the contralateral limb, which occurred 100 ± 50 ms after slip onset. Thus the time between touchdown of slipping limb to liftoff of contralateral limb was on average 185 ms. Pre-slip step length was calculated as the difference between the heel markers of the slipping foot (right) and the contralateral foot (left) at the touchdown of the slipping foot. At liftoff of the contralateral foot, the BOS kinematics were obtained from its heel marker. There was no relative motion between the heel marker of the slipping foot and the moveable plate from touchdown to that instant.

Statistics. The outcome for each subject on each trial was treated as a nominal variable and was assigned values of either 0 (balance loss) or 1 (no balance loss). Non-parametric statistics would therefore be best suitable to analyze the changes in incidence
(%) of outcome across trials and between groups (Pavol et al. 2002). Thus, the Cochran’s Q test, with post-hoc Chi-square tests were performed to test changes in incidence of balance loss with repeated slip trials. Chi-square ($\chi^2$) tests were also performed to test changes in incidence of balance loss on each trial between the acquisition and follow-up sessions. A mixed factor repeated measures ANOVA was performed with gait stability as the dependent variable, and with the two sessions and the two time instants (pre and post-slip) as independent fixed factors, and with slip trials (S1-S4) as the repeated independent factor. Only four subjects had good data on the fifth slip trial of the acquisition session. Thus only the first 4 trials were included in the ANOVA; results of the 5th slip trial between sessions and within sessions between trials were analyzed using t-tests. Planned t-tests were conducted on pre- and post-slip stability between the 1st slip trials of the two sessions and between the 1st slip of the follow-up and last slip of the acquisition sessions. Significant main effects of the ANOVA were followed up with simple effects (one-way repeated measures ANOVA for each event for each session) and planned t-tests between consecutive trials. Significant interactions were resolved using event x session ANOVA’s between consecutive trials with post-hoc t-tests. Two-way repeated measures ANOVA’s with session as the fixed and trial as the repeated factor were conducted on pre- and post-slip $X_{COM/BOS}$, and $\dot{X}_{COM/BOS}$. Significant results were followed-up with planned comparisons between sessions for each trial and between consecutive trials within each session. Paired t-tests between consecutive trials within each session, and between sessions for each trial were also conducted on 1) pre-slip step length, 2) post-slip BOS displacement, and 3) velocity.

Separate Bonferroni’s corrections were applied to the post-hoc t tests. Absolute p values between 0.05 and 0.001 for significant t-test comparisons were reported. A significance level of 0.05 was used for all the analyses. Analyses were performed using SPSS (Chicago, IL).
Results

Long-term retention of gait stability

All subjects exhibited a loss of balance on the 1st slip experience both during the initial acquisition and at the 12-month follow-up. In the acquisition session with repeated slip exposure, subjects were able to significantly reduce the incidence of backwards balance loss by the 3rd slip trial (p < 0.05, Figure 2). In the follow-up session, the reduction in incidence of balance loss, however, was much more rapid, i.e., from 100% in the 1st slip to only 13% in the 2nd slip (p < 0.05, Figure 2). Such differences in outcomes were directly related to gait stability. Results of the mixed-factor repeated measures ANOVA indicated a significant main effect of session, [F(1,24) = 7.25, p = 0.01], and a significant main effect of trial [F(4,96) = 40.70, p < 0.001]. The relationship between pre- and post-slip stability changed over trials [trial by event interaction: F(4,96) = 23.44, p < 0.001]. Significant main effects of the ANOVA (and interaction) are discussed in detail in the following sections.

Retention of gait stability observed in the 1st slip

During the follow-up session, subjects exhibited a significantly greater pre-slip stability on the regular as well as the 1st slip exposure compared to the 1st slip exposure of the acquisition session (p = 0.01 for both) (Figure 3a, b). This significantly greater pre-slip stability was achieved by a significantly anterior XCOM/BOS on the follow-up session (p < 0.05) (Figure 4). There was no change in pre-slip gait stability (at touchdown of the slipping limb) between the last exposure of the acquisition session and the 1st exposure of the follow-up (p > 0.10). As shown in Figure 5a, the COM state mean for Trial 1 on the follow-up session was closer to the threshold than for the acquisition session, as reflected in the greater pre-slip stability. There was no significant change in post-slip stability (at liftoff of the contralateral limb) on the regular and 1st slip trial between the two sessions (p = 0.37, p = 0.10). Post-slip stability on the 1st follow-up slip was significantly lower compared to the last slip of the acquisition session (p < 0.05) (Figure 3b, e).
There was no change in pre-slip stability from the regular walking to the 1st slip trial, but post-slip stability between the two trials decreased significantly [significant event x trial interaction: F(1,28) = 124.49, p < 0.001] for both sessions [significant trial x session interaction: F(1,28) = 1.97, p > 0.10] with stability at liftoff (post-slip) being greater than stability at touchdown (pre-slip) during the regular trial (p < 0.001), but post-slip stability being significantly lower than pre-slip stability for the 1st slip trial (p < 0.001) for both sessions [session x event interaction: F(1,28) = 0.64, p > 0.10] (Figure 3a, b).

**Rapid re-acquisition with repeated slip exposure**

As shown in Figure 3 b-d, there was a significant increase in pre-slip stability for the acquisition session [F(4,5) = 7.69, p = 0.001] and the follow-up session [F(4,7) = 12.37, p < 0.001] with repeated slip exposure. A significant increase in pre-slip stability for the acquisition session was found from slip trials 1 to 2 (p = 0.02) and 2 to 3 (p = 0.04) compared to the majority of the re-acquisition completed in the 2nd trial (p = 0.01) for the follow-up session, with no change thereafter (p > 0.10). The subjects had significantly greater pre-slip stability on the second slip trial of the follow-up session than they had during the acquisition session (p = 0.04).

Trial-to-trial increase in pre-slip stability for both sessions was achieved by an anterior shift in the XCOM/BOS [main effect trial: F(4,48) = 25.46, p < 0.001, no significant session x trial interaction, p > 0.10], from the 1st to the second (p < 0.001) and second to the third slip trial (p = 0.02). The XCOM/BOS was, however, significantly anterior on the repeated slips for the follow-up session [main effect session: F(1,12) = 6.10, p = 0.03] (Figure 4, 5a). There was no change in X COM/BOS (gait velocity) between trials and sessions (main effect: p > 0.10 for both).

The trial-to-trial increase in post-slip stability with repeated slip exposure between the two sessions resembled the pre-slip change pattern with a significant increase in post-slip stability for the acquisition session [F(4,5) = 15.18, p < 0.001] and the follow-up session [F(4,7) = 19.89, p < 0.001] with repeated slip exposure. In the acquisition session, these subjects required two repeated slips to continuously improve post-onset stability (p <
0.01 for increase from trial 1 to 2, and 2 to 3). In the follow-up session, these same subjects only needed one repeated slip for the re-acquisition (p < 0.001 for increase from trial 1 to 2). Similar to the pre-slip stability, the subjects had a significantly greater post-slip stability on the second slip trial of the follow-up session as compared to the acquisition session (p < 0.01, Figure 3c).

There was a significantly greater increase in post-slip stability as compared to pre-slip stability from the 1st to the 2nd slip [event by trial interaction: F(1,28) = 35.75, p < 0.001] and 2nd to the 3rd slip [event x trial interaction: F(1,28) = 11.53, p = 0.002, Figure 3c, d], during the acquisition session but not thereafter (significant session x event interaction, p > 0.10, Figure 3d, e). The re-acquisition in post-slip stability for the follow-up session on the 2nd slip trial after exposure to the 1st slip was so much greater than the original acquisition session [session x event interaction, F(1,28) = 4.39, p = 0.04], such that there were no further improvements thereafter. A similar increased improvement in post-slip stability had developed by the third trial in the initial acquisition session [session x event interaction: F(1,28) = 4.85, p = 0.04, Figure 3d). The mechanisms for improving stability at liftoff (post-slip) were similar for both sessions; these were achieved by anteriorly shifting the $X_{COM/BOS}$ [main effect trial: F(4,48) = 24.60, p < 0.001; session x trial interaction: p > 0.10] and increasing the $X_{COM/BOS}$ [main effect trial: F(4,48) = 29.52, p < 0.001]. Nevertheless, the $X_{COM/BOS}$ was significantly more anterior in the follow-up session than it was in the acquisition session [main effect session: F(1,12) = 6.10, p = 0.03]. For both the sessions, on the 1st slip trial, the $X_{COM/BOS}$ was significantly posterior compared to the regular walking trial due to the unexpected nature of the slip (p < 0.001), followed by a significant anterior shift in the 2nd (p < 0.001) and the 3rd slip (p = 0.002, Figure 6a). The $X_{COM/BOS}$ exhibited no significant main effect of session with repeated slips [F(1,12) = 1.40, p >0.10], but it had a session x trial interaction (p = 0.07). The $X_{COM/BOS}$ was traveling significantly slower on the 1st slip trial compared to regular walking due to the slip (p < 0.001), for both sessions but was followed by a significant increase in the 2nd (p < 0.001) and the 3rd slip (p = 0.01). The increase in $X_{COM/BOS}$ from trial 2 to 3 was significantly
greater in the follow-up session than it was in the acquisition session (session x trial interaction: p < 0.05, Figure 6b). Figure 5b shows that by the 2nd slip trial of the follow-up session, the mean of the COM state relative to the BOS, at post-slip liftoff, lies above the computationally predicted stability threshold for backward balance loss. This shift, however, occurs by the 3rd slip trial in the acquisition session. It must also be noted that while pre-slip adaptive change in COM state stability was characterized by an anterior shift towards the backward balance loss threshold, involving only a position change relative to the BOS (Figure 5a), post-slip adaptive changes were associated with an anterior and upward shift, i.e., with increase in relative velocity as well (Figure 5b).

With repeated slip exposure, there was a significant reduction in post-slip BOS displacement and velocity for the acquisition session, with a significant reduction in displacement and velocity during the 2nd slip (p = 0.044 and p = 0.037, respectively) and in velocity only during the 3rd slip (p = 0.02, Figure 7a, b). In comparison, in the follow-up session, there was a significant reduction in BOS displacement and velocity only in the 2nd slip (p = 0.014 and p = 0.006, respectively), with its displacement and velocity significantly lower than that in the acquisition session (p = 0.045 and p = 0.01, respectively; Figure 7a, b).

**Discussion**

Our results indicated that a single acquisition session could not produce a sustainable long-term effect that could reduce backward balance loss in the very first slip after 12 months. Improvement was observed in pre-slip gait stability during the 1st slip of follow-up session, but it was apparently insufficient, as all subjects exhibited a loss of balance on the follow-up session, similar to that seen on the 1st slip of the acquisition session. Nevertheless, a learning effect was most noticeable on the 2nd slip, in which backward balance loss was reduced by 87%, a significant improvement compared to the same trial in the acquisition session.

**Retention of gait stability observed in the 1st slip**
Consistent with our hypothesis, subjects showed retention of pre-slip stability, which remained the same in the 1st slip of the follow-up session as the last slip of the acquisition session, and both these were significantly improved compared to the 1st slip of the acquisition session. This improved gait stability was achieved by the same mechanism as in the acquisition session, namely by anteriorly shifting the $X_{\text{COM/BOS}}$. Contrary to our expectation, however, the subjects were unable to retain improvement in the follow-up session for the post-slip stability that they had acquired at the end of the acquisition session. It appeared that this increase in pre-slip stability from an improved feedforward mechanism (Bhatt et al. 2005a; Pai et al. 2003) was insufficient to significantly alter reactive post-slip stability and hence the final outcome. It is worth noting that there was a definite trace of the training effect; we observed that the subjects tended to be more stable post-slip upon the first slip exposure in the follow-up session than they had been in the acquisition session, with a probability level of post-slip stability close to 0.10. This gain in stability may be considered a partial retention. Yet, it appears that the combination of the pre-slip retention and partial post-slip retention could not alter the final outcome of the 1st slip in the follow-up session.

We postulate that the CNS was attempting to recall and execute the stable COM state representation acquired during the acquisition session, but only partially succeeded due to uncertainty when encountering the 1st slip, and possibly the deterioration in motor memory over the 12-month period. When the perturbation could not be fully compensated by pre-slip feedforward adjustment, the CNS must then have relied on feedback mechanisms following slip onset to improve stability. These findings suggest that while the retention of feedforward control affecting gait stability prior to slip onset was evident, the training effect on the reactive response, which could heavily rely on feedback control when perturbation was unexpected, might be more difficult to retain over a prolonged period. To the best of our knowledge, these findings illustrated for the first time the significance of the reactive response and the possible difficulties of retaining the training effect on feedback control. It is also possible that a single acquisition session that included 5 repetitions was not sufficiently intense to elicit
sustainable changes, although it was apparently effective and successful in reducing the incidence of backward balance loss from 100% to 0% by the 5th trial.

Rapid re-acquisition with repeated slip exposure

Our results indicate that with training, the subjects were able to rapidly reduce balance loss incidence after the 1st slip. It was noteworthy that although there was a significant increase in stability from the 1st to the 2nd slip during acquisition session, it was insufficient resulting in a high balance loss incidence (75%) on that trial. The significant reduction (by 87%) in balance loss on the 2nd slip trial of the follow-up session could be explained by the significant and sufficient stability improvements during this session.

This achievement was made by improving both pre- and post-slip stability, whereby the post-slip improvement was significantly greater than the pre-slip improvements, and likely resulted from improvements made in both feedforward and feedback control. Our findings support previous findings indicating that increasing one’s stability during the period of transition from double to single stance following slip onset is critical for prevention of balance loss (Bhatt et al. 2005a; You et al. 2001). The control of balance can be characterized by the control of the COM state with respect to the BOS ($i.e.$, $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$). During this period, the CNS controls stability by altering the state of the COM through the control of individual segment positions and their velocities, especially that of the upper body that carries the majority of body mass. The CNS may alternatively choose to closely regulate and adjust the BOS state, which is dictated by the lower limb kinematics. Previous findings have indicated that braking impulse exerted under the slipping limb is the single best predictor of BOS velocity (Bhatt et al. 2005a). The trial-to-trial adaptive changes in gait stability with repeated slip exposure for both sessions were achieved by both an anterior shift in $X_{COM/BOS}$ and an increase in forward $\dot{X}_{COM/BOS}$. However, the significantly improved stability on trial 2 of the follow-up session was achieved due to a significantly greater increase in $\dot{X}_{COM/BOS}$ achieved by a significantly lower BOS velocity. Such changes in BOS velocity following slip onset could in part be explained by feedforward adjustments in pre-slip gait pattern ($e.g.$ foot angle, step length, heel velocity) (Bhatt et al. 2005a; Lockhart et al. 2003) that influence
post-slip kinetics (braking impulse) and the BOS perturbation intensity (Bhatt et al. 2005a).

Feedforward control would require prior experience and learning of the environmental constraints, as well as the physiological properties and limitations of the system to be controlled. Interestingly, the experimental results can be fully accounted for if we assume that probability of balance loss and stability limits are predictable, and that the feedforward stability control that the CNS employs must require an internal representation of the stability limits (Pai et al. 2003). An improved internal representation derived from repeated slip exposure could then improve pre-slip feedforward control, which would have significant impact on post-slip reactive response. Successful feedforward control would likely reduce or even eliminate the need for feedback correction in the reactive response. Earlier evidence from perturbations studies also support this notion that the CNS builds or updates internal representation for the feedforward control of stability based on experience and anticipation. For example, when the perturbation type during stance changes from toes-up rotation to backward translation, subjects still show some postural strategies adapted to the previous perturbation (Horak and Nashner 1986). Similarly, when subjects anticipate a smaller perturbation but experience a larger one, they still show smaller magnitude responses (Horak et al. 1989; Timmann and Horak 1997). These responses could be pre-selected before the perturbation began due to formation of a “postural set” (Horak et al. 1989; Timmann and Horak 1997).

Insufficient retention in post-slip stability on the 1st slip in the follow-up session may also indicate that the CNS may have altered the acquired internal representation of the stable gait pattern, as the result of interference from performance of their preferred regular gait (Del Rey 1989), reinforced over the extensive 12-month period during activities of daily living. Preferred gait patterns are often associated with minimum energy expenditure (Cavagna et al. 1976; Griffin et al. 2003), which may not be a primary concern when one is to avoid backward loss of balance. Therefore, it is possible that the gait patterns acquired for resisting backward balance loss are not reinforced sufficiently during regular
gait of daily living, and continue to deteriorate over time. Our findings revealed, however, that once a stable postural response had been acquired, the refreshment of motor memory following a 12-month interval would not take nearly as long as the original acquisition (Neumann and Ammons 1957).

It should be noted that the neurophysiological mechanisms underlying long-term retention for posture and gait adaptation are far from fully understood; moreover, current understanding of related phenomena at the behavior level is limited. Long-term retention has been well observed in the context of practice-related performance changes in skilled voluntary movements (Newell 1991). These studies have seldom examined retention at or 12 months later with a single acquisition session. Systematic study of the effects of a single acquisition session at predetermined time intervals would be very costly to conduct. The present study charted the temporal boundary of such investigation, where a single acquisition session resulting in only partial longer-term retention in motor behavior was insufficient to yield significant results. The absence of long-term retention in reactive (post-slip) stability on the 1st slip may be due to the low intensity of the acquisition session. This indicates that long-term structural changes could not be brought about after a mere 5 repetitions. Our acquisition session to improve gait stability was highly efficient and successful in temporarily reducing incidence of backward balance loss. This success is attributable, at least in part, to the potentially threatening nature of the perturbation employed. In fact, severe injury or even death is the most serious consequence of loss of balance and resulting falls among older adults (Cummings et al. 1990; Stalenhoef et al. 1999). Slip during gait is one of the leading contributors for these causes (Luukinen et al. 2000; Michelson et al. 1995).

In summary, the present study revealed that gait stability improvements acquired in a single acquisition session can be retained in varying degrees over a period of 12 months, though no degree of retention was sufficient to alter the outcome of balance control when slip occurred for the first time. These improvements, however, could be more quickly refreshed than they were acquired. Based on the findings of the present study, our conclusion is that future investigations should focus on the effect of retention shorter than
the 12-month interval and possibly also on the effectiveness of stimulus intensity.

Studies that take into account stimulus intensity should include the determination of the
minimal number of repetitions and acquisition sessions required to produce a retainable
effect in behavior.

Acknowledgments This work was supported by 2R01 AG16727. The authors thank
Jason Wening, Debbie Espy for assisting in data collection and processing, Edward Wang
for statistical consultation, and Dr. James Girsch and Kathy Breving for editing of the
text.
References


Figure Legends

Figure 1: (a) The instantaneous gait stability for an instantaneous center of mass (COM) state (diamond) is the shortest distance (double-headed arrow) between the boundary and the COM state. (b) COM state trajectories for a slip and a non-slip trial for a representative subject from the acquisition session. The thick gray line represents the boundary for backward loss of balance. The time course of the COM state trajectory is indicated by small black arrows for the slip trial (solid line) and by gray arrows for the non-slip trial (dotted line). Anteroposterior COM position and velocity are normalized to foot length and $\sqrt{g \times h}$, respectively, where $g$ is acceleration due to gravity, and $h$ is the body height. The model predicts that a person whose COM state is less stable at slip onset (star) is more likely to undergo a subsequent backward loss of balance (as indicated by the solid line below the threshold) and a touch down posterior to slipping foot.

Figure 2: Decrease in number of balance losses (LOB) from 1st to 4th slip trials for the acquisition (T1, thin-lined pattern bar) and the one-year follow-up (T2, thick-lined patterned bar) sessions. The corresponding registrations of no balance losses for each trial are indicated by thin and thick-lined open bars respectively for the acquisition and follow-up sessions.

Figure 3: Gait stability (means ± 1 SD) at pre-slip touchdown of slipping limb (TD, open symbols) and post-slip liftoff of contralateral limb (LO, closed symbols) from the acquisition (circles) and the follow-up (squares) sessions, for regular walking and 1st through 4th slip trials (S-1 to S-4). Significant differences in gait stability (for both pre- and post-slip events) between the two sessions for each trial are indicated (*, p < 0.05). Note the differential increase from pre- to post-slip stability for the follow-up session compared to the acquisition session on the 2nd slip trial (S-2), indicated by the presence of interaction session by event interaction (S x E).

Figure 4: Means (± 1 SD) of anteriorposterior center of mass (COM) position relative to the base of support (BOS) ($X_{COMBOS}$) normalized to foot length at pre-slip touchdown of the slipping limb from the acquisition (open circles) and follow-up sessions (closed
circles) for the regular walking and 1\textsuperscript{st} through 4\textsuperscript{th} slip trials (S-1 to S-4). Significant between session changes, and trial-to-trial adaptive changes with respect to the preceding trial are indicated by #, and *, respectively (p < 0.05).

Figure 5: The distribution of center of mass states relative to base of support (X\textsubscript{COM/BOS}, \dot{X}\textsubscript{COM/BOS}) at (a) pre-slip touchdown of slipping limb and (b) post-slip liftoff of contralateral limb, for all trials classified into balance loss (LOB, open symbols) and no-balance loss (NLOB, filled symbols) for the acquisition (circles) and follow-up (squares) sessions. COM state means (± SD) for slip trials 1 (unfilled), 2 (half-filled) and 4 (filled) from both sessions are plotted as well.

Figure 6. Means (± 1 SD) of COM state with respect to the BOS (X\textsubscript{COM/BOS}, \dot{X}\textsubscript{COM/BOS}) at post-slip liftoff of the contralateral limb from the acquisition (open circles) and follow-up sessions (closed circles) for the regular walking and 1\textsuperscript{st} to 4\textsuperscript{th} slip trials (S-1 to S-4). Significant between session differences, and adaptive changes with respect to preceding trials are indicated by #, and *, respectively (p < 0.05).

Figure 7. Means (± 1 SD) of the state of the BOS (slipping foot heel displacement, X\textsubscript{BOS}, and its velocity, \dot{X}\textsubscript{BOS}) at liftoff of the contralateral limb from the acquisition (open circles) and follow-up session (closed circles) for the regular walking and 1\textsuperscript{st} to 3\textsuperscript{rd} slip trials (S-1 to S-3). Significant between session differences, and adaptive changes with respect to preceding trials are indicated by #, and *, respectively (p < 0.05).
Figures

Figure 1
Figure 2

- Trials: S-1, S-2, S-3, S-4
- Number of subjects: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10
- Loss of balance
- No loss of balance

Legend:
- Loss of balance: crossed lines
- No loss of balance: solid lines

T1, T2 (>1 yr)
Figure 3

Trials

Figure 4
Figure 5

(a) Pre-slip - Touchdown of slipping limb

(b) Post-slip - Liftoff of contralateral limb
Figure 6

Figure 7