Retention of Adaptive Control Over Varying Intervals: Prevention of Slip-Induced Backward Balance Loss During Gait

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Submitted 16 November 2005; accepted in final form 3 January 2006

Bhatt, T., E. Wang, and Y.-C. Pai. Retention of adaptive control over varying intervals: prevention of slip-induced backward balance loss during gait. J Neurophysiol 95: 2913–2922, 2006. First published January 11, 2006; doi:10.1152/jn.01211.2005. Stability improvements made in a single acquisition session with merely five slips in walking are sufficient to prevent backward balance loss (BLOB) at the end of session, but not after 12 mo. 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 ≤4 mo. Twenty-four young subjects were exposed to blocks of slip, nonslip, and both types of trials during walking at their preferred speed in the acquisition session. In each of the four follow-up sessions around 1 wk, 2 wk, 1 mo, and 4 mo later, these same subjects experienced only a single slip after eight to 13 unperturbed walking trials in an otherwise identical setup. Gait stability was obtained as the shortest distance of whether a slip occurred. During retest sessions, subjects’ preslip stability was not different from that in S24, with improvements converging to a steady state, that enabled all of the subjects to avoid BLOB, regardless of whether a slip occurred. During retest sessions, subjects’ preslip stability was not different from that in S24, but was greater than that in S1. Their postslip stability was also greater than that in S1 but less than that in S24, resulting in BLOB at a 40% level. No difference was made in a single acquisition session with merely five slips in walking and Nashner 1986; Horak et al. 1989; Mummel et al. 1998; Nashner 1976, 1982), 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. 2006; 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 thus 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. 2006). Although 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 (2002) demonstrated retention of the acquired changes in magnitude of body sway to calf vibrations during stance of up to 1 mo. 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 five 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.

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INTRODUCTION

An essential function of the 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 1976, 1982), 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. 2006; 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.

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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 preslip stability improvements 12 mo later, which were related to feedforward control, but not necessarily the postslip stability improvements, which were possibly related to the feedback mechanisms (Bhatt and Pai 2005). Consequently, a single acquisition session consisting of merely five repeated slips in walking is sufficient at the end of reactive session, to prevent backward loss of balance, although this is not the case after 12 mo. Although the only instruction they received throughout the original acquisition and the retest 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 subsequently retainable on the first slip reexposure, with a more intense acquisition session and at shorter reevaluation intervals than those 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 <12 mo. We extended the "repeated slip paradigm" (Bhatt et al. 2006) to include a greater number of trials and a combination of blocks of slip, nonslip (NS), and both types of trials during self-selected walking. We hypothesized that during the acquisition session, subjects would rapidly improve their pre- and postslip stability and later reach a steady state, regardless of whether a slip occurs, resulting in a significantly reduced incidence of balance loss as compared with the first slip exposure. After retesting 1 wk, 2 wk, 1 mo, and 4 mo later, we hypothesized that they would exhibit a significantly greater pre- and postslip-onset stability and a lower incidence of balance loss compared with 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 yr, 12 males) participated in the study after being screened for exclusionary factors such as neurological, musculoskeletal, cardiopulmonary, other systemic disorders, and selected drug usage. Of the 24 subjects who participated in the acquisition session only 22 subjects completed the three follow-up sessions (F1, F2, and F3) and only 17 subjects participated in the last follow-up session (F4). Before participation, all subjects gave their informed consent as approved by the Institutional Review Board.

**Experimental setup**

Two sliding devices were placed side by side. Each was capable of inducing a slip with a low-friction, nonmotorized movable top plate (65 × 30 cm, 2.7 kg) mounted on a frame with linear bearings 2.5 m long, which was then bolted onto two force platforms (OR6-5-1000, AMTI, Newton, MA). These devices were locked and embedded in a 7-m walkway and hidden by the stationary decal platforms surrounding it. The actual coefficient of friction obtained from ground reaction force (GRF) measurements was <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 speed, and fine-tuned based on the height and step lengths of the subject (Bhatt et al. 2005).

The slips were induced by a computer-controlled release mechanism that unlocked one of the movable platforms at the beginning of each trial without the knowledge of the subject. The second plate was released on touchdown of the trailing limb when the preset loading threshold was exceeded. Once released, the movable 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, Austin, TX) was used for on-line 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 on suspension.

**Acquisition session**

In the acquisition session, the subjects were told that they would walk for a block of trials at their preferred manner and 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 adjust each subject’s starting position so that his or her future slipping (right) foot would land entirely on the movable plate at touchdown. All subjects were able to take at least three steps before stepping on the movable 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 first 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 eight repeated slips (S1–S8), a block of three nonslips (NS1–NS3), another block of eight slips (S9–S16), followed by the second block of three nonslip trials (NS4–NS6) and a final block of 15 mixed trials (Fig. 1). The randomly selected sequence of the mix block was consistent for each subject: S17–S18, NS7–NS8, S19, NS9, S20, NS10, S21–S22, NS11–NS12, S23, NS13, and S24 (Fig. 1). Although previous studies have established that three to five repeated slips are sufficient for adaptive
improvements in balance loss (Bhatt et al. 2006; 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 four follow-up sessions (F1–F4) conducted at intervals around 1 wk, 2 wk, 1 mo, and 4 mo. 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 induced always last, after the subjects had walked a randomly selected number of walking trials at their preferred manner and speed, anywhere from a minimum of eight 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, whereas one marker was attached to each movable platform. Marker coordinates were recorded at 120 Hz using a six-camera motion-capture system (Motion Analysis, Santa Rosa, CA). Marker displacement data were low-pass filtered at marker-specific optimal cutoff 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 arising from 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. 2005; 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 $>0$). More positive values indicate greater stability against backward balance loss (Bhatt et al. 2005; Pai et al. 2003).

**Pre- and postslip 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. Preslip stability was measured and noted at touchdown of the slipping limb. Postslip 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. 2006) we analyzed the changes in the $X_{COM/BOS}$ at preslip touchdown of the slipping limb and the BOS velocity ($X_{BOS}$). The latter was obtained from the heel marker of the slipping limb at postslip liftoff of the contralateral limb. The $X_{COM/BOS}$ at pre-slip touchdown of the slipping limb was also used to examine differences in gait speed between sessions.

When the contralateral limb landed posterior to the sliding heel with negative values in postslip 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 postslip step length were classified as “no loss of balance” trials, in which protective stepping was not needed and forward progression was continued.

**Statistics**

Trial-to-trial changes in pre- and postslip onset stability within 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 fifth trial of the first slipping block was included in the analysis similar to previous studies (Bhatt et al. 2006; 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 four slips obtained from each of the four sessions from F1 to F4 were included in the retention analysis. Two, one-way ANOVAs for repeated measures were performed with pre- and postslip stability as the dependent variables and the slip trials (S1 and S24; F1–F4) as the repeated factor (session). The main effects of the ANOVA were followed with planned t-test between consecutive trials included in the analysis and between S1 and S24 and each of the four 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 preslip $X_{COM/BOS}$ and $X_{COM/BOS}$ and postslip $X_{BOS}$. 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 postslip stability with “group” as the independent factor and “session” as the repeated factor (S1 and S24, and three 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-test between consecutive trials. Because five individual subjects failed to return for the last follow-up session, separate paired t-tests were used to estimate the changes occurring between F3 and F4. A
Acquisition

There was a main effect of trial for both pre- \([F(6,126) = 14.33, P < 0.001]\) and postslip stability \([F(6,126) = 47.33, P < 0.001]\). As in Fig. 2A, with repeated slip exposure, subjects showed a significant increase in preslip stability by S5 compared with the first unexpected slip in S1, with no further increase in that block \((P > 0.10\) between S5 and S8). Subjects demonstrated a significantly lower stability during the first reslip exposure in S9 than in S8 of the previous block \((P = 0.002)\). By the next slip in S10, preslip stability improved and was maintained for the remaining slip block. The preslip 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 postslip stability were similar to changes in preslip stability during the first block of repeated slip exposure, showing a significant increase in postslip stability from S1 to S5 \((P < 0.001)\) and no change between S5 and S8 \((P > 0.10)\) (Fig. 2B). However, postslip stability on the first slip in S1 was much lower compared with the preceding regular walking trial. In the first slip of the second block of slips (S9), postslip stability was lower compared with the last slip of the first block (S8) \((P = 0.02)\). It improved in S10, however, and this increase was similarly maintained for the remaining slips of the block. Postslip 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., nonslip trials, postslip stability was greater than the slip trials and even greater than the natural walking trials preceding the first slip \((P < 0.05)\) (Fig. 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 \([F(6,22) = 86.79, P < 0.001]\) (Fig. 3). The incidence of balance loss reduced to the 8% level by S5 \((P < 0.001)\) and remained at that level until S8 \((P > 0.10\) between S5 and S8). On S9 after three nonslip 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 \((P < 0.05)\). After another block of three nonslip 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 four of the last five slip exposures (Fig. 3).

Retention

There was a significant main effect of session on preslip stability \([F(5,30) = 10.00, P < 0.001]\) and postslip stability.

![Fig. 2. Group means of (A) pre- and (B) postslip-onset stability during the acquisition session. Nat = unperturbed, self-selected “natural” walking trials preceding the first slip; NS = a block of 3 nonslip trials after a block of slip trials. Data points with SD bars are the trials included in statistical analysis. More positive values indicate greater stability. 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, \(*P < 0.05\). 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.](http://jn.physiology.org/)

![Fig. 3. Histogram displaying incidence of backward balance loss (in percentage) for the acquisition session. Nat = walking trials at self-selected “natural” speed; NS = nonslip trials where the movable/slipping plate was in a locked position (open bars). Acquisition session included 2 slipping blocks S1–S8 and S9–S16. Mixed block consisted of interspersed slip and nonslip 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.](http://jn.physiology.org/)
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, Fig. 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 compared with the 100% incidence in the first slip of the acquisition session \(P < 0.001\) for all comparisons) (Fig. 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 \(P > 0.10\) (Fig. 4B).

The changes in preslip stability were accounted for by changes in \(X_{COM/BOS}\) \(F(5,80) = 8.8, P < 0.001\) (Fig. 5A). There was a significant anterior shift in \(X_{COM/BOS}\) from S1 to S24 of the acquisition session \((P < 0.001\). The \(X_{COM/BOS}\) 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 \(X_{COM/BOS}\)) between the consecutive follow-up sessions, \(P > 0.10\). There was no significant change in gait speed at preslip touchdown of the slipping foot \(X_{COM/BOS}\) between sessions \(F(5,80) = 0.98, P > 0.10\). The changes in postslip stability were accounted for by changes in \(X_{BOS}\) \(F(5,80) = 26.56, P < 0.001\). There was a significant decrease in \(X_{BOS}\) from S1 to S24 \((P < 0.001\), although this decrease was not maintained on the first follow-up session that showed a significant increase in \(X_{BOS}\) compared with S24 \((P < 0.005)\). There was no further change in \(X_{BOS}\) between the consecutive follow-up sessions \(P > 0.10\) for all paired planned comparisons between consecutive sessions) (Fig. 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 \(\times\) 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 compared with S1 (main effect of session: \(F(4,28) = 21.00, P < 0.001\), and no difference in their postslip stability compared with S24 \((P > 0.05, Fig. 6A)\). Conversely, the group with “poor” retention \((n = 3)\) had no difference in stability on follow-up sessions (F1, F2, and F3) compared with S1 \((P > 0.10\) for all compar-

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**Figures and Table**

**Fig. 4.** A: changes in preslip and postslip 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.

**Fig. 5.** Group means ± SD of (A) preslip COM position relative to BOS \((X_{COM/BOS})\) normalized to foot length and (B) BOS velocity \((X_{BOS})\) 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). ***\(P < 0.001\); *\(P < 0.05\).
It also had much worse postslip stability on the follow-up sessions than that in S24 ($P < 0.05$ for F1, F2, and F3, and $P = 0.12$ for F4; Fig. 6A), resulting in an inability to prevent balance loss incidence on the follow-up sessions (Fig. 6B). Further post hoc analysis indicated that the “poor” retention group had less of a “flat foot” with a greater foot angle and a greater postslip BOS velocity on F1 compared with S24 (Foot angle: $11.0 \pm 4.0^\circ$ on S24 vs. $14.95 \pm 4.97^\circ$ on F1, $P = 0.07$; BOS velocity: $0.3 \pm 0.13$ m/s on S24 vs. $0.7 \pm 0.11$ m/s on F1, $P = 0.05$), contributing toward lower postslip stability. The group that had various degrees of retention ($n = 11$) had significantly greater postslip 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 postslip stability was found for this group during the follow-up sessions compared with the last slip in acquisition session (between S24 and F1, $P = 0.07$; and F2, $P = 0.05$; and F3, $P = 0.05$, Fig. 6A), associated with a wide range of balance recovery outcomes (Fig. 6B).

There appeared 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 (Fig. 6C). None of the subjects in the “good” retention group experienced more than two balance losses during the 24 slip trials, compared with that experienced by seven subjects (63%) in the “moderate” retention group and one 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 ($y = 2.2857x + 11.564, R^2 = 0.37, P < 0.01$, Fig. 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 postslip gait stability for at least 4 mo after the initial acquisition session. The retained improvement in these variables was lower, however, compared with 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 with 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 postslip stability, leading to a rapid decrease in incidence of balance loss. After they experienced mixed blocks of trials of slips and nonslips, a steady state was reached for the COM stability and likewise a low incidence of balance loss (Figs. 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 and Iqbal 1999; Pai et al. 2003). 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 ability to neutralize the perturbation—would enable one to maintain stability regardless of whether a slip occurs, thus 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. 2006). The fact that all young adults tested while walking at their preferred speed experienced backward loss of balance during the first slip exposure (Bhatt and Pai 2005; Bhatt et al. 2006) indicates that the desired movement strategy is not inherent and must be acquired through motor training even among healthy individuals. Because of its ecological implication, such stability training would be warranted, especially among those individuals with an elevated risk of falls.

This paradigm of “slip–nonslip–reslip” used in the acquisition session has extended our previous findings on adaptation to forward slips during gait (Bhatt et al. 2006). 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 that the CNS is anticipating to experience (Bhatt et al. 2006; Vetter and Wolpert 2000). On reexposure 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 preprogramming a desirable COM-state trajectory, which would be stable under a variety of environmental contexts.

Retention

Our results supported the second hypothesis that subjects showed a significantly greater pre- and postslip stability on all the follow-up sessions compared with the first slip of the acquisition session. Contrary to our next hypothesis, however, subjects exhibited complete retention only in preslip stability, whereas the average postslip stability was considerably lower in the follow-up sessions compared with 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 with nearly 40%, Fig. 4B), but was higher than the last exposure of the acquisition session. Our results confirmed previous findings that indicated that subjects were able to completely retain adaptive improvements in preslip stability up to a period of ≥12 mo 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 retest is done at intervals <12 mo, postslip stability is also retained.

Our analysis indicates that intersubject variability could be an important factor in affecting postacquisition retention. Post hoc analysis was able to identify subgroups of individuals with various abilities to retain what has been acquired. One subgroup of eight subjects had little or no failure during the 4-mo period, indicating that it is possible to completely retain improvement in postslip stability with no balance loss in the follow-up sessions. Conversely, another subgroup of three subjects completely failed to retain the training effect during the 4-mo 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 further investigated other identifiable factors, within the realms of this study, that 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, that 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 with their last acquisition slip. This difference could have led to a higher slip velocity and thus lower postslip stability (Bhatt et al. 2006).

The intensity of training could also have played a role, affecting the variability in postslip stability. This paradigm may have provided sufficient stimuli to train one subgroup of eight 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 (accounting for about 37% of variability between incidence of balance loss between acquisition and follow-up sessions; Fig. 6D). Our data showed that individuals who did well in the initial acquisition session were inclined to perform better in the follow-up sessions and vice 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 “overlearning” 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 preslip stability are achieved, arguably, through feedforward control, causing an anterior shift in COM position with shortening of preslip step length (Bhatt et al. 2006). Similarly, our results indicated that changes in preslip 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. 2006). 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 during 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 before and after 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.

After repeated slips, adaptive improvements in postslip stability could possibly occur as the result of 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 preslip 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. 2006). Similarly, our results indicate that increases in postslip stability from the first slip to the last slip of the acquisition trial were achieved by significant reductions in BOS velocity. Also, the reduction in postslip stability on the follow-up session correlated strongly with reductions in BOS velocity. Notably, in the absence of a perturbation during the nonslip trials, the COM state at liftoff was still more stable against slip-related backward balance loss than natural walking before the first slip exposure. Taken together, these findings further support the postulation of strong feedforward influence on postslip stability proposed in previous studies (Bhatt et al. 2006).

The decreased performance in postslip stability on the follow-up sessions may also be affected by subjects’ inability to retain the minimal feedback-based reactive control, still needed postslip, to control the BOS perturbation intensity once perturbation onset occurs (Bhatt et al. 2006). 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 ≤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 sensorimotor 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. 2006; Pai et al. 2003), is probably associated with the shift from reliance on short- and long-loop reflex pathways within the spinal cord and brain stem (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 Brashers-Krug 1997; Shadmehr and Holcomb 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 sensorimotor relationships involving higher control systems and conscious control and feedforward mechanisms could be easily consolidated and stored (Tjernstrom et al. 2002). This contrasts with sensorimotor 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 postslip 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 compared with that of our previous attempt, relying on only five 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 reinforced 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 “reconsolidated” (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 reconsolidate this memory, showing poor performance in a subsequent follow-up session. This could explain the random frequency of balance loss between subjects and sessions (Fig. 6B). The relatively complete retention within feedforward control in preslip stability could have involved the explicit or episodic learning associated with spatial memory that 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). Nonetheless, episodic learning and improved knowledge of the slip were apparently not sufficient for keeping some from falling backward. Failure in proper interaction with the procedural system or inappropriate activation could account for failures in retention associated with postslip stability. Although 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 among individuals in the “moderate” and “poor” retention categories. Our results reflect that these few individuals probably had more problems in long-term memory compared with the immediate near-term memory because they were all able to adapt but not able to have “good” retention. Also, the role individual cognitive capacity plays in retaining the stability improvements 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 subgroups of individuals (mediocre to poor motor learners) who easily or eventually (i.e., with some difficulty) adapted well but failed to retain the acquired skills, possibly arising from 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 whether 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-mo period. Our previous results support this notion of “priming” where all subjects lost their balance in the first unexpected slip after ≥12 mo, but it was perhaps sufficient to facilitate a rapid reacquisition, resulting in a significantly lower incidence on balance loss on the second slip (Bhatt and Pai 2005).

In summary, the present study revealed that gait stability improvements acquired with an enhanced single acquisition session, consisting of multiple blocks of slips, can be sufficiently retained for a period of 7 days over at least 4 mo, to alter the outcome of balance control when exposed to a 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. Finally, 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.

ACKNOWLEDGMENTS
The authors thank J. Sun, D. Espy, P. Wong, and K. Brevig for assisting in data collection and processing, and S. Shehabi for editing the text.

GRANTS
This work was supported by National Institute on Aging Grant 2R01 AG-16727 to Y.-C. Pai.

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