CAN OBSERVATIONAL TRAINING SUBSTITUTE MOTOR TRAINING IN PREVENTING BACKWARD BALANCE LOSS FOLLOWING AN UNEXPECTED SLIP DURING WALKING?

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Abstract

A person’s awareness of potential slippery walking conditions induces a cautious gait pattern. The purposes of this study were to determine whether neuromechanical changes associated with such cognitive conditioning are sufficient to alter the outcome of a slip and whether the effects of such conditioning are comparable to those of motor training. Prior to their own first slip exposure, 18 young subjects watched videos and slides demonstrating where and how the slip would occur and how people adapted to repeated-slip exposure (OBSERVE). The outcomes of the first slip exposure experienced by another 16 subjects who did not receive any such information were used as controls (NAÏVE). The latter subjects subsequently experienced an additional 23 slips and thus served in a dual-role as the motor training group (MOTOR). Gait stability as measured against backward loss of balance (BLOB) was obtained for pre- and post-slip instances. A protective step landing posterior to the slipping-limb identified each BLOB outcome. The OBSERVE group had a greater post-slip stability and lower slip displacement and velocity than the NAÏVE group. However, such effects were insufficient to prevent balance loss (100% BLOB). The MOTOR group showed significantly better performance on the last training slip (0% BLOB) than did the OBSERVE group. The results indicated that updating the cognitive centers of the CNS with awareness and perceptual knowledge through observational training can yield tangible benefits. Nonetheless, observation could not replace the task-specific motor training that adaptively updated the internal representations of stability limits for prevention of BLOB.
Introduction

The ability of the central nervous system (CNS) to adopt successful movement strategies for controlling the motion state (i.e., instantaneous position and velocity) of a person’s center of mass (COM) in relation to his body’s base of support (BOS) – and to do so in the presence of changing environmental and task constraints – is essential for maintaining both mobility and stability. The CNS undergoes protective adaptations when prior knowledge of conditions is available sufficiently ahead of time; for example, advance awareness of obstacles decreases the likelihood of tripping (Patla et al. 1991). Similarly, it is known that awareness of potential slippery conditions induces a cautious gait pattern (Cham and Redfern 2002; Heiden et al. 2006). It has been suggested that such proactive gait adjustments can reduce the likelihood of an actual slip even in the presence of a suddenly emerging low-friction surface condition. Mere awareness of a possible slip creates only kinematic changes as the slipping limb approaches the ground (landing with a flatter foot and flexed knee) (Cham and Redfern 2002; Heiden et al. 2006). However, these changes restricted to kinematics at pre-slip touchdown may not adequately prepare a person to respond to backward loss of balance and falls. Thus it is unknown whether these gait modifications can sufficiently prevent or reduce the likelihood of backward loss of balance or falls on slippery surfaces – or during artificially-induced slips under controlled conditions.

Our recent studies have examined the effectiveness of training subjects by means of repeated exposure to slips produced in a laboratory environment mimicking “real-life” situations (Bhatt et al. 2006a; Bhatt et al. 2006b; Pai et al. 2003; Pavol et al. 2004). Such training fortifies a person’s neuromuscular protective mechanisms as they affect the causal relationship between reduction of balance loss and improvement of stability (Pai et al. 2003). This improvement can result from the increased control of the braking impulse, changes in landing-foot and knee angle, and associated muscular activation level and timing. Stability is here operationally defined as *ability* to restore balance without resorting to alteration of a subject’s BOS following an externally imposed perturbation or even during volitional movement (Pai 2003; Pai and Patton 1997; Pai and Iqbal 1999; Wu et al. 2007; Yang et al. 2007). The results, in response to repeated-slip training during
gait, have revealed improvements in both the pre- and post-slip control of stability. Pre-slip stability was obtained at pre-slip touchdown of the leading slipping limb; post-slip stability was measured at the instant of post-slip liftoff of the contralateral limb. Furthermore, our results indicated that the subjects who were able to increase their post-slip stability to a level above the computational threshold for backward loss of balance post-training were indeed able to prevent a backward loss of balance (Bhatt et al. 2006a; Bhatt et al. 2006b). These adaptive improvements in stability resulted mainly from decreases in the velocity of the post-slip base of support (BOS) following the onset of a slip, which was influenced by feed-forward controlled, proactive adjustments in pre-slip stability and in slipping-limb landing kinematics immediately prior to slip onset (Bhatt et al. 2006a). It was proposed that the updating of the internal representation of stability limits for backward loss of balance using the trial-to-trial feedback led to similar improvements in performance even under unpredictable environmental conditions (i.e., slip or no-slip) (Pai et al. 2003).

The results yielded by motor training through repeated slip exposure, though clearly beneficial, may nevertheless be cumbersome and expensive to implement; this method also involves a slight risk factor. In contrast, observational training (or modeling), widely used for sport-related skill acquisition (Scully 1988; Williams 1987), could be an attractive cost-effective and safe alternative training approach. This method involves demonstrating the skill (in person or via visual aids) in a way that permits learners to observe the essential component actions of the skill and to acquire the qualitative features of the various elements or subtasks involved in successful task performance (Ashford et al. 2006; Williams 1987). Such training can have very significant clinical implications. Slip-related falls are the leading cause of injury-related hospitalization or death across a spectrum of individuals ranging from the healthy elderly to physically impaired persons of all ages (Baker and Harvey 1985). Observational training could be easily, safely, and economically implemented as an alternative to motor training, including repeated slip exposure, for prevention of these dangerous falls.
It has been suggested that the direct observation of a model (i.e., a trained person presenting a demonstration for other persons) provides information about spatiotemporal relationships within or between limbs or between the limbs and the environment (Scully 1988; Scully and Newell 1985). This perceived “relative motion” information permits a person to anticipate and prepare the pattern of coordination required by a particular movement activity/task, enabling him to approximate the observed movement leading to changes in motor outcome (Scully and Newell 1985). Thus, such learning usually provided through audio-visual means or verbally could help develop an accurate motor schema of the task to be executed, leading to improved performance during the execution of the actual task. It is unclear, however, whether observational training by itself – without the actual sensorimotor experience – can lead to successful adaptation to slip perturbation and subsequent prevention of backward loss of balance upon an actual slip.

The purpose of this study was therefore to determine whether observational training could improve the motor performance upon the first, novel slip and if so, whether its effect would be comparable to that induced by motor training. Observational training was provided through video and still images of successful adaptation to a slip perturbation. Motor training exposed naive subjects, after their first unexpected slip (whose outcome also served as a control), to blocks of repeated slips followed by a randomized paradigm of slips mixed with non-slip trials. We first hypothesized that observational training (OBSERVE) would enable subjects to demonstrate a more successful performance, indicated by a higher stability (pre- and post-slip) and a lower incidence of backward loss of balance, than that demonstrated by naive subjects (NAÏVE) who had received no prior instruction on how to resist the slip perturbation. Second, we hypothesized that the performance improvements exhibited by the OBSERVE subjects would be similar to those induced by motor training (MOTOR). Thus we expected that subjects in the OBSERVE group would show stability and incidence of balance loss at levels similar to those demonstrated on the last training slip by subjects in the MOTOR group.
Methods

Subjects. Thirty-four young subjects (26 ± 5 years, 21 males) participated in the study after being screened for exclusionary factors including neurological, musculoskeletal, cardiopulmonary, other systemic disorders, and selected drug usage. The subjects were randomly divided into two groups: NAÏVE (not receiving any prior information about slip conditions, n = 16) and OBSERVE (receiving observational training on successful adaptation to slip perturbation, n = 18). Following the first slip exposure, the NAÏVE group received motor training, described in detail below (MOTOR). Prior to their participation, all subjects gave informed consent as approved by the Institutional Review Board.

Experimental set-up. Slips were induced by means of a device consisting of two components. The non-movable component comprised a metal beam structure (2.50 × 0.30 × 0.21 m) anchored to the top of two rectangular force plates (OR6-5-1000, AMTI, Newton, MA). The movable component comprised a metal plate (0.65 × 0.30 × 0.006 m, 2.6kg) and its support system (Yang and Pai 2007). This plate can be either locked for regular walking trials or released to simulate a slip. The friction coefficient of the device was consistently below 0.05, within its pre-set maximum travel distance. The device was embedded in a seven-meter walkway and hidden by the stationary decoy platforms surrounding it.

Slips were induced by a computer-controlled release mechanism that unlocked the moveable platform at the beginning of each trial without the knowledge of the subject. Once released, the moveable platform was free to slide on the linear bearings for up to a maximum travel distance of 1.5 m on the right and 0.9 m on the left before locking into the end position. A computer program written in LabView (National Instruments Inc., Austin, TX) was used for online monitoring of the GRF and generation of the lock-release signal. 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 subjects’ knees could not touch the surface of the floor upon suspension.
Protocol

The subjects in the NAÏVE group performed 10 regular walking trials at a self-selected speed; in these trials, they were instructed to walk in their ordinary manner and told that they “may or may not be slipped” on any trial. They were also told that upon the occurrence of a slip, they should try to recover their balance and continue walking. Without revealing the purpose, the experimenter adjusted each subject’s starting position after each trial, so that his or her slipping (right) foot would land entirely on the moveable plate at touchdown. All subjects were able to take at least three steps before stepping on the moveable plate. The first slip was induced on the 11th trial, without explicit warning or practice. The subjects were not aware of which trial would include a slip, where on the walkway the slip would occur, nor what its characteristics would be.

Following the first slip, the same subjects were exposed to a repeated slip training paradigm (MOTOR group). The subjects were told that they “may or may not” be exposed to slipping on the subsequent trials; they were given the same instructions as before the slip. The entire training paradigm, including the first trial, consists of a block of 8 repeated slips (S1-S8), a block of 3 non-slip trials (NS1-NS3), another block of 8 slips (S9-16), a second block of 3 non-slip trials (NS4-NS6), and a final block of 15 mixed trials. The sequence of the mixed block of trials was consistent for each subject: S17-S18, NS7-NS8, S19, NS9, S20, NS10, S21-S22, NS11-NS12, S23, NS13, and S24 (Bhatt et al. 2006b).

All subjects in the observational training group (OBSERVE) watched a video sequence consisting of 5 repeated slip trials (5 video clips – each trial representing one clip), first at normal play speed and then in slow motion after a short break. All subjects watched the video sequence at their pace one more time. Total training time was between 15 and 30 minutes. The model video sequence showed a typical adaptation made by young subjects; the sequence was selected from our existing archives and used with permission of the subject who appeared in it. The video showed the adaptive progression from backward loss of balances upon the first and second slips (Figure 1a) to successful
adaptation for preventing such balance loss and maintaining forward progression (Bhatt et al. 2006a), upon the third through fifth slip exposures (Figure 1b) (5 trials total). The video also made clear to the subjects exactly where and how the slip occurs. A typical loss of balance trial demonstrated a significantly long and fast displacement of the moveable plate, with the subjects exhibiting a protective stepping response and with the trailing foot landing posterior to the slipping foot. In the “no loss of balance” trials, the subjects minimized the moveable plate displacement; the trailing limb landed anterior to the slipping limb in what appeared to be a natural walking pattern. At the end of each video sequence, the experimenter informed the subject of the outcome of the slip perturbation shown on the screen (i.e., “loss of balance” versus “no loss of balance” outcome). Subjects then watched slides (snapshots) of still images of the model at the instant of touchdown on the moveable plate. The subjects were shown 5 slides – each taken from the above mentioned 5 video trials the subjects viewed. These slides illustrated the foot and knee angles on the first slip (first slide) and subsequently the adaptive changes in foot and knee angles at touchdown during walking after exposure to slips. Half of the subjects (N = 10, NO VERBAL CUE) had to infer how to adapt to the slips from the video and the snap shots. The other half of the subjects (N = 8, VERBAL CUE) were given “more” training via verbal instructions when they were shown the snapshot of a subject from an adapted trial demonstrating a flatfoot landing with flexion at the knee. The experimenter pointed out these aspects on the screen and provided verbal instructions to explain to subjects that “walking with a flatfoot landing and a more bent knee could prevent a slip and backward loss of balance.” While subjects knew where the slip shown in the video would occur, they had no knowledge of the exact trial when it would occur. After this observational training, subjects proceeded to the testing, which, apart from the aforementioned visual demonstration, was identical in setting and protocol to that for the NAÏVE group, up to and including the first slip.

Data collection and reduction. A set of twenty-four full body light reflective markers was attached to the bilateral upper and lower extremities and the torso, while one marker was attached to each moveable platform. Marker coordinates were recorded at 120 Hz using a 6-camera motion capture system (Motion Analysis Corporation, Santa
Rosa, CA). Marker displacement data were low-pass filtered at marker-specific optimal cut-off frequencies (range: 4.5-9 Hz) using a recursive second-order Butterworth Filter (Winter 2005). Force plate, electromyography (EMG), 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, EMG, and motion data were time-synchronized at the time of data collection.

Surface electrodes of Ag-AgCl with inbuilt pre-amplifiers of gain x35 were used to record EMG activity from 4 muscles of each leg including the gastrocnemius, tibialis anterior (TA), vastus lateralis, and biceps femoris (BF). For clarity, we have included only two representative muscles from these recordings. The BF and TA of the slipping limb were chosen, because they are the first ones to be activated on the very first trial following a forward perturbation (Marigold and Patla 2002). These two muscles are typically involved in correcting the displaced COM over the BOS following a forward perturbation (Ferber et al. 2002; Marigold and Patla 2002). Furthermore, the BF is shown to be proactively activated before slip onset under conditions of prior awareness of the likelihood of slipping or post-slip experience (Heiden et al. 2006). Electrode placement was set up according to that described in the literature (Winter 1991). EMG signals from the preamplifiers were fed into an eight channel amplifier (CyberAmp 380, Axon Instruments, Inc, Union City, California). The CyberAmp 380 performed pre-rectification filtering of the raw EMG signals using a 4th order low-pass Bessel filter with a 300 Hz cut-off frequency and also amplified the signals (pre-filter gain = x1, post-filter gain = x100). The signals were then fed into the A/D converter. EMG signals were digitally band pass filtered at 10-200 Hz following data collection. All digitized EMG signals were full-wave rectified and low pass-filtered using a 2nd order dual pass (zero lag) Butterworth filter with a 50 Hz cut-off frequency (Grasso et al. 1868; Irwin et al. 2005). For each subject, the three regular walking trials preceding the first slip trial on each side (right and left) were ensemble-averaged for each muscle and time-aligned from heel strike of the slipping limb on the moveable plate to the next 500 ms (i.e., heel strike = time 0 ms). The EMG recording of the slip trials was also time-aligned similarly from heel strike of the slipping limb. The time-aligned EMG profile of each of the slip trials
was subtracted from the ensemble average of regular walking to yield the \textit{subtracted profile}, for each subject, which was used for further analysis (Figure 2).

**Neuromechanical control of gait stability.** The COM position and its 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; Pavol et al. 2002). The position of the COM in the anteroposterior direction was expressed relative to the rear of the BOS ($X_{\text{COM/BOS}}$) of the most recent foot to touchdown (\textit{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 ($\dot{X}_{\text{COM/BOS}}$) and normalized as a dimensionless fraction of $\sqrt{gh}$ (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 loss of balance under slip conditions (Pai and Iqbal 1999). Stability was defined as the shortest distance from this predicted boundary for backward loss of balance to the instantaneous COM state (Bhatt et al. 2005; Pai et al. 2003). The model simulation predicts that backward loss of balance \textit{must} occur for COM states below the threshold (\textit{i.e.}, stability < 0). Backward loss of balance \textit{should not} occur when the stability measure is above the predicted value (\textit{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 balance loss under slipping conditions (Bhatt et al. 2005; Pai et al. 2003).

Analysis was restricted to the anteroposterior direction. The instances of step liftoff and touchdown were identified from the vertical ground reaction forces. The outcome of slip was classified as a fall if the hip midpoint descended below 15\% of body height from the minimum hip height during normal walking trials. Trials in which the average force on the safety harness was less than 4.5\% of body weight over any 1-second period after the slip onset were classified as a recovery. When the contra-lateral limb landed posterior to the sliding heel with negative values in post-slip step length during the slip, the recovery
trials were classified as “backward balance loss trials with protective stepping.” Conversely, trials with the contra-lateral limb landing anterior to the sliding heel and positive post-slip step length were classified as “no loss of balance” trials, in which protective stepping was not needed and forward progression not disrupted. Pre-slip stability was measured and noted at touchdown of the slipping limb. Post-slip stability was recorded at liftoff of the contra-lateral limb. The time between touchdown of the slipping limb to liftoff of the contralateral limb was on average 180 ms.

To further understand the contributing factors for adaptive changes in the COM stability, based on the findings from previous studies (Bhatt and Pai 2005; Bhatt et al. 2006a), we analyzed the factors contributing to the neuromechanical control of the slipping BOS/slipping limb. The neuromechanical control of the slipping limb encompassed three categories: slipping kinematics, kinetics, and muscle activation pattern. They were as follows respectively: BOS displacement ($X_{BOS}$) and the change in its velocity ($\dot{X}_{BOS}$); braking impulse under the right limb; and the post-slip EMG integrals of TA and BF were analyzed. In addition, the right foot and knee angle at pre-slip touchdown and pre-slip EMG integral of BF were analyzed (Cham and Redfern 2002; Heiden et al. 2006). The braking impulse in this text measured the posterior (i.e., braking) force exerted on the slipping foot integrated over the chosen time period. It is indicative of the adaptive changes and is known to substantially alter the BOS/slip kinematics (i.e., displacement and velocity) (Bhatt et al. 2005; Marigold and Patla 2002). Given that a greater braking impulse can better reduce the peak slipping velocity, the braking impulse signifies the reactive kinetic response on the subject’s part to control the BOS movement upon the first unexpected slip.

The BOS displacement and velocity were obtained from the heel marker trajectory of the slipping limb from its point of touchdown (heel strike) to the point of post-slip liftoff of the contra-lateral limb following the slip. There was no relative motion between the moveable plate marker and the slipping limb marker after its touchdown (Bhatt et al. 2006a). The braking impulse under the slipping limb was obtained as the integral of the ground reaction force in the anterior-posterior direction from touchdown of the slipping
limb to post-slip liftoff of the contralateral limb after correcting for weight of the moveable plate (Yang and Pai 2007). The post-slip-onset EMG integrals were obtained respectively by integrating the \textit{subtracted profile} from 100-300 ms post-heel strike of the slipping limb (Bhatt and Pai In preparation). Mechanical slip-onset (motion detection of the moveable plate based on its velocity) for the first slip trial for all subjects was between 30-50 ms. This period was chosen to account for the mechanical delay of the slip onset and was consistent with the prevailing standard for analyzing onset latencies of forward support-surface perturbations, which typically range between 90-200 ms post-heel strike (Cham and Redfern 2001; Ferber et al. 2002; Marigold and Patla 2002; Tang and Woollacott 1998; Tang et al. 1998). Given that burst duration typically lasts about 200 ms (Marigold and Patla 2002; Tang et al. 1998), the period of 100-300 ms following heel strike was considered sufficient to enable us to capture a robust activation (Figure 2; solid box demonstrates the integration window). The integrated EMG activity of the \textit{subtracted profile} from each muscle was normalized by dividing it with the corresponding integrated EMG activity of the ensemble average of walking trials during the same time period – \textit{i.e.}, \((\text{IEMG during slip} – \text{Average IEMG during walking})/\text{Average IEMG during walking})\). The normalized EMG integrals (IEMG) were used for statistical analysis.

Based on the mechanical onset time of the moveable plate, it was postulated that the EMG activity in the BF from heel strike to 100 ms would allow us to quantify any \textit{robust proactive} changes that were the result of observational learning. The \textit{“pre-slip”} activity was quantified and normalized in this period as above (Figure 2; dashed box demonstrates the integration window). The foot angle was obtained as the angle between the foot (line joining the heel and 5\textsuperscript{th} metatarsal) and the horizontal plane at the instant of touchdown of the slipping limb. Knee angle was obtained as external angle between the thigh and shank at the same instant.

\textbf{Statistics.} The first slip trial of the group receiving no prior slip information (NAÏVE group), the last training slip trial (24\textsuperscript{th}) of the same subjects (MOTOR group), and the first slip trial of the subjects receiving observational training (OBSERVE group) were
included in the analysis. Planned comparisons were performed between the OBSERVE and the NAÏVE groups and between the OBSERVE and MOTOR groups, using parametric and non-parametric tests. The Mann Whitney U test was performed to test for significant differences in incidence of falls and backward balance loss between the groups. The outcome for each subject on each trial was determined and categorized as either as a fall (value = 0) or recovery (value = 1). The recovery outcome for each subject on each trial was further determined and categorized as either balance loss (value = 0) or no balance loss (value = 1). Independent t-tests were performed to test for significant differences in stability (pre- and post-slip) and BOS control that encompassed the slipping kinematics (post-slip BOS displacement (XBOS) and velocity (ẊBOS)), the kinetics (braking impulse under slipping limb during double stance), the post-slip EMG integrals from the slipping limb, and the pre-slip limb control (slipping limb foot and knee angle at pre-slip touchdown and “pre-slip” EMG integrals). No comparisons were made between the NAÏVE and MOTOR group, as these findings have been previously published (Bhatt et al. 2006b). Absolute p values are reported for all the planned comparisons performed. A significance level of 0.05 was used for all the analyses. Analyses were performed using SPSS (Chicago, IL).

Results
There was no significant difference in the outcome of performance, i.e., incidence of backward balance loss, between the OBSERVE and the NAÏVE group (p > 0.10), and all subjects in both groups exhibited a backward balance loss on the first slip exposure. (Because the receiving or not receiving of additional verbal instructions did not change incidence of balance loss and fall or any of the measured variables (p > 0.10), the two sub groups in the OBSERVE group were combined for statistical analysis and comparison with the NAÏVE and MOTOR groups.) In contrast, motor training was able to significantly reduce incidence of backward balance loss, and none of the subjects in that group exhibited a backward balance loss on the last (24th) slip (p < 0.0001, between OBSERVE and MOTOR). The incidence of falls was lower as compared to that of balance loss in both groups. In the NAÏVE group 3/16 (18%) subjects experienced a fall, whereas in the OBSERVE group 1/18 (5%) subjects experienced a fall. There were no
falls in the MOTOR group. There was no statistical difference detected in fall incidence between the groups (p > 0.10 for all comparisons).

There was no significant difference in pre-slip stability between the OBSERVE and NAIVE groups (p = 0.57), nor was there any between the OBSERVE and MOTOR groups (p = 0.08) (Figure 3a). There was no difference in pre-slip foot and knee angles between the OBSERVE and NAÏVE groups (p > 0.10 for both angles). However, the MOTOR group had a significantly lower pre-slip foot angle (flat foot landing) and a significantly greater knee flexion (p < 0.001) as compared to the OBSERVE group (Figure 4a). Similarly, there was no difference in pre-slip BF activity between the OBSERVE and NAÏVE groups (p > 0.10); however, the MOTOR group had significantly greater pre-slip BF activation than did the OBSERVE group (p = 0.007) (Figure 4b).

Although post-slip stability was greater in the OBSERVE group than in the NAÏVE group (p = 0.03), such improvement was not sufficient to prevent backward balance loss. However, there was a significantly greater improvement in the MOTOR group as compared to the OBSERVE group; its mean post-slip stability had a positive value, indicating stability above the threshold for triggering backward balance loss (dashed line in Figure 3b). Such a difference in stability between the OBSERVE and the MOTOR groups directly accounted for the difference in performance outcome (0% versus 100% backward balance loss).

The OBSERVE group also displayed a better control of the BOS displacement than did the NAÏVE group, with displacement of the slip being significantly lower in the OBSERVE compared to the NAÏVE (p = 0.04). However, there was no significant difference in velocity (p = 0.06). Similarly, there was no significant difference in the impulse generated beneath the slipping limb and the post-slip activations in TA and BF between the OBSERVE and NAÏVE groups (p = 0.10 for impulse and p = 0.15 for both muscles). There was no difference in the displacement between the MOTOR and the OBSERVE group (p = 0.09); however, the subjects in the MOTOR group were able to achieve a significantly greater reduction in their slip velocity than was the OBSERVE
group (p < 0.001) (Figure 5a). The braking impulse beneath the slipping limb in the MOTOR group was lower than that in the OBSERVE group; however, this difference did not reach a significant level (p = 0.06) (Figure 5b). The activations in the TA and BF were significantly lower in the MOTOR group than in the OBSERVE group (p = 0.001 for TA and p = 0.04 for BF) (Figure 5c & d).

Discussion
This study provided direct evidence that the OBSERVE group achieved a slightly better performance in response to an actual novel slip than did the control NAÏVE group, after the latter group underwent observational training through visual modeling of successful adaptation to slips. Observational learning could indeed significantly improve some aspects of performance (e.g., control of slip displacement and improvement in post-slip stability) that are major determinants of balance loss outcome. Although such results lend support to our first hypothesis, most of the improvements were not sufficient to reach the significance level, nor were they sufficient to cross the thresholds that are required to alter the outcome of recovery. On the other hand, the results did not support our second hypothesis, namely that the motor training was clearly more effective than the observational training in preventing backward balance loss resulting from an unexpected slips during walking. The observational training could not by itself be substituted for motor training, in as much as the effect of the latter was significantly superior to that of the former.

Past studies have demonstrated that awareness of potential slippery conditions can elicit a cautious gait pattern, leading to a subject’s taking short steps and a having greater knee flexion and a flat-footed landing at the moment of touchdown (Cham and Redfern 2002; Heiden et al. 2006; Marigold and Patla 2002). The subjects in the OBSERVE group also displayed tendencies to greater knee flexion and flat-footed landings, but such changes did not reach the significance level. In addition, these studies did not report the recovery outcome using the same criteria to identify backward balance loss that were used in the present study. It is unclear whether the changes in knee flexion and flat-footed landing
altered the recovery outcome in those studies. It must be noted that the improvements in neuromechanical control of slip achieved via observational learning, though insufficient to alter outcome under such a large-scale perturbation, might have prevented backward balance loss if the slip distance was shorter than that allowed in the present study. Even though observational learning was insufficient to prevent a person from falling backward (i.e. evident as backward balance loss), it may be able to reduce the incidence of an actual fall by enabling execution of an effective and successful protective step. However, the current study did not have sufficient power to significantly differentiate the fall incidence between groups due to the small percentage of this outcome.

One of the postulated reasons for accidental balance losses and falls is the unpredictable nature of perturbation and the lack of adequate preparation (Pai et al. 2003). Based on such logic, awareness of potential environmental hazards via the posting of warning signs, for example, should minimize the incidence of falls. Although subjects were aware of where and how a slip would occur and how to respond to these circumstances, our findings indicate that such cognitive preparation would be insufficient to alter the outcome. It seems also reasonable to expect that if cognitive training on “how to” prevent backward balance loss is provided (kinematic strategy), the outcome could be better than a mere observation of the adapted strategy. None of the subjects provided with explicit knowledge of kinematic improvements performed differently as compared to the subjects who had no such knowledge. Since the OBSERVE group was shown only videos and pictures of adaptations, it is reasonable to expect that they would change only their kinematics, which is probably in itself insufficient to alter outcome of balance loss. If the subjects had been trained in how subjects changed their kinetics during adaptation, their performance during the first slip could have improved. Though it is more difficult to train subjects to change their kinetics via observation, verbal cueing can nonetheless be provided by asking the subjects to reduce their landing force; i.e., by advising them to “land very gently”.

To mimic the accidental nature of a slip in real-life situations, the condition of the forthcoming trial (and thus the timing of the occurrence of a slip) was not provided to any
group in the present study. It is possible that the CNS could require both “spatial” (i.e., where and how to occur) and “temporal” (i.e., when to occur) awareness of the context of an impending slip, in order to elicit significant proactive changes in gait pattern.

Nonetheless, it is quite possible that accurate “temporal” awareness possessed by the observational training group caused no change in the recovery outcome shown in the present study. Our recent results show that accurate awareness of both temporal and spatial aspects of slip conditions can indeed induce gait adaptations such as a flatfoot landing as compared to the unaware condition. There were no changes in pre-slip foot angle and pre-slip stability between the natural walking trial (nonslip control), prior to the first slip, and the first slip itself. However, such changes were still insufficient to alter outcome for the large-scale slip (Bhatt and Pai In preparation).

Our results thus support the notion that implicit (visual) gains or explicit (visual + verbal instructions) gains from observational knowledge on successful adaptation to slip conditions were not comparable to changes in gait pattern and limb control from motor training (actual experience) (Bhatt et al. 2006a; Heiden et al. 2006; Marigold and Patla 2002). Like previous findings (Bhatt et al. 2006a; Bhatt et al. 2006b), our findings suggested that repeated slip training induced kinematic changes (increased knee flexion and flat foot landing) and muscle activation changes (increase in pre-slip BF activity) in slipping limb as the limb approached the floor. Such changes further affected the limb-surface interaction (reduced braking impulse) and the slip intensity (reduced displacement and velocity), increasing the post-slip stability and subsequently improving outcome.

It must be noted that the mechanism used to induce slips via the sliding device does not precisely reproduce the conditions of “actual slips,” which could affect the slipping response. For example, the plate used in the device adds inertia to the foot (Yang and Pai 2007) that does not exist in “free” slipping; this, then, could possibly reduce the peak velocity of the slip. In addition, a slippery flat surface could allow a “free” slip with medial or lateral displacement that had been constrained in the present study. Nevertheless, our pilot results indicate that our device had a coefficient of friction very
similar to that of a liquid contaminant, and the response adopted by the subjects to prevent balance loss was comparable under these two environmental conditions. Furthermore, the “slipping response” obtained from our device (moveable plate kinematic profiles, peak velocity, and time to peak velocity (Bhatt et al. 2005)) is comparable to that recorded in the literature that examines responses to “free” slips induced by lubricant material (i.e. liquid contaminant) (Lockhart et al. 2003; Redfern et al. 2001; You et al. 2001). Finally, the pre-slip proactive alteration observed in the OBSERVE and the NAÏVE groups would definitely not be affected by the differences in slip-inducing mechanisms.

Observational training or “mental imitation” of a model is a common motor acquisition procedure in which persons assimilate information necessary to mimic actions of others (Ashford et al. 2006; William et al. 1999). Recent evidence suggests that observational training can improve some aspects of the movement control (e.g., amplitude and velocity) more than the overall movement outcome *per se* (Ashford et al. 2006; Hayes et al. 2006). Our results indicate that although observational knowledge did not alter overall outcome, it enabled subjects to produce additional control over the slip. For example, the OBSERVE group tended to exhibit a greater post-slip COM state stability as compared to the NAÏVE group, which was achieved via increased reactive control of the base of support; this in turn resulted in significantly lower displacement and velocity profiles of the base of support (heel and moveable plate) and a reduced braking impulse under the slipping limb. Such improved reactive control could have been influenced by the feed-forward controlled tendency of flatfoot landing, with increased knee flexion and higher BF activation levels demonstrated by the OBSERVE group.

Environmentally-induced falls are indeed a major health concern in all populations, but this is especially so for older adults; the number of falls increases exponentially with increasing age (Baker and Harvey 1985; Holbrook et al. 1984; Tinetti et al. 1988). Slip-related falls account for about 20% of all falls and are amongst the most debilitating (Luukinen et al. 2000). Though the observational training provided in the current form was insufficient to alter the outcome of the first (and novel) slip, it may still be combined
to improve the effectiveness of the motor training. The subjects can be allowed to re-play the video as many times as they would like within a pre-set length of time, watching it at any speed they choose. Such combined training could have a substantial impact on performance variables, most significantly perhaps one leading to a significant reduction in fall incidence. Such training can be then used as an adjunct to traditional rehabilitation amongst the healthy older adults and even in populations with gait and balance impairments.

It should be emphasized that though observational training has definite merits and could be an excellent adjunct, it cannot replace motor training. All the measured variables in the current study showed the exceptional benefits that can be derived from motor training as compared to observational training. It is possible that the effect of observational training is task-dependent; for instance, ballistic skills predominantly using feed-forward controlled open loop programs (e.g., swinging a golf ball) would benefit more than would continuous or rhythmic tasks such as juggling balls or, as in this case, locomotor-balance control. Subjects can build or update the context estimate of an “internal model” or representation within the CNS for successful task execution, as applied to an open looped task using the knowledge of context conditions gained via the observational training, in absence of actual sensory feedback provided by the task performance (Vetter and Wolpert 2000). In addition, the visuo-perceptual (and/or audio-perceptual, if verbal instructions are provided) information, both kinematic and kinetic, acquired via the observational training could assist effective task execution. However, for continuous tasks, performance depends heavily on the online feedback obtained; thus actual feedback practice or training could offer greater benefit than observation. Nonetheless, practice-dependent motor training must continue to have a unique place in the acquisition of any skill – just as the proprioceptive information gained from actual practice has a unique and essential role in building of the sensorimotor models during skill acquisition.

The use of observational training in this study to promote locomotor-balance skill acquisition can be still justified because such training is known to involve the higher cognitive-perceptual and sensory-associative areas of the brain, which have abundant connections with the motor areas (Iacoboni et al. 1999; Rizzolatti et al. 2001; Vogt and
Roland 2007). Recent studies have revealed a hierarchical organization of areas of the brain responsible for control of posture and locomotion with activation of cortical and subcortical areas during actual locomotion. This is comparable to those involved in imagined locomotion (Jahn et al. 2004; Miyai et al. 2001). Imagined locomotion also activates additional areas responsible for visuospatial navigation (Jahn et al. 2004). Further emerging evidence indicates a strong cortical influence on the posture and locomotion centers during perturbed locomotion or under challenging environmental conditions (Drew et al. 2004; Kably and Drew 1998; Matsuyama et al. 2004). Thus, the positive changes associated with observational training could be explained by these mechanisms and could still, to some extent, promote the acquisition of such a locomotor-balance skill.

The higher success rate of motor training as compared to observational training probably suggests a weak or even absent communication of the “acquired knowledge” to the respective sensori-motor planning and execution areas within the CNS. On the other hand, trial-to-trial proprioceptive feedback about the COM state stability’s being gained from the task-related experience seems to possess faster and more direct access to an error comparator within the sensorimotor areas (Wolpert and Ghahramani 2000), which are responsible for building or updating the motor plan for subsequent encounters with a similar environmental situation. Such proprioceptive information from the slip-induced trunk and limb motion also enables greater prediction of future sensory consequences of the motor plan and execution commands than that probably provided by the visual processing (spatial memory of the slip location and model’s responses to slips).

In conclusion, our results indicate that observational training intended to promote successful adaptation to slipping was able by itself to yield tangible improvements in the control of stability against slip-related backward balance loss, although such improvements were significantly less than those achieved through motor training. Consequently, observational training alone was not sufficient, as was motor training, to alter performance outcome of balance recovery from unexpected exposure to an actual slip. The results further suggest that direct task-related experience may be required by
the CNS for updating or modifying motor plan for execution of successful strategies for prevention of backward balance upon perturbation such as slip.

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References


Figure Legends

Figure 1. Sample video-frame sequences used for observational training. a) A backward loss of balance outcome, and b) a successful adaptation strategy with a no balance loss outcome following a slip after stepping on the low-friction platform that was released unexpectedly during prescribed gait. Note: images 1-4 corresponded to the events of onset of slip, liftoff of contralateral limb, pre-touchdown of contralateral foot, and touchdown of contralateral foot. The position of the foot and knee angles at touchdown is indicated by vertical and horizontal arrows respectively in a-1 and b-1. The vertical arrows in frames 2-4 indicate the initial position of the slipping heel for reference.

Figure 2. The rectified EMG profiles of the biceps femoris (BF) and tibialis anterior (TA) muscles from a representative first slip trial from the NAÏVE group (i.e. first unexpected slip) in the UNAWR and AWR groups. Shown for each muscle are the EMG profiles in volts (V) of the ensemble average of three walking trials (solid thin line) and the subtracted slip trial profile (dashed thick line) for the slipping limb. The rectified EMG profile of each slip trial was subtracted from that of the ensemble average profile of the three regular walking trials after aligning them to touchdown of the slipping limb (time = 0 seconds) to obtain the subtracted profile. Also shown for the same limb are the profiles of the base support (BOS) velocity (\( \dot{X}_{BOS} \)) in meters per second (m/s) and vertical ground reaction force (\( F_Z \)) in Newtons (N). Solid vertical lines in chronological sequence indicate instants of touchdown (TD) of the slipping limb, mechanical slip onset (Onset), post-slip liftoff (LO) of the contralateral limb, and touchdown of the contralateral limb. The limb of touchdown of liftoff is indicated by -R for right and -L for left. The time interval for integration for “pre-slip” activity (only obtained in BF) is indicated by a solid gray box and that for “post-slip” activity by dashed gray box.

Figure 3. Comparison of group means (+ 1 SD) of (b) pre-slip and (c) post-slip stability between the observational training group (OBSERVE, filled bar, lined) and its control group (NAÏVE on first unexpected slip, open bar) and the motor training group (MOTOR with a total of 24 slip exposures, filled bar, crossed). The values for comparisons for \( 0.001 < p < 0.10 \) are indicated. The level for comparisons with \( p > 0.10 \) has not been
indicated. Also shown with the horizontal dashed line is the stability threshold for prediction of backward loss of balance, with mean stability values < 0 indicating a backward loss of balance (Bhatt et al. 2006a; Pai and Iqbal 1999). Note, less negative values of stability indicate greater stability. Also, the right (slipping) foot as base of support and stability boundary for slipping condition were the conventions consistently used for both pre-slip and post-slip stability calculations. No comparisons were made between the NAÏVE and MOTOR group, as these findings would not be different from those previously published (Bhatt et al. 2006b).

Figure 4. Comparison of group means (+ 1 SD) for (a) pre-slip foot and knee angles and (b) “pre-slip” integrated electromyography activity (IEMG) of the biceps femoris for the NAÏVE (open bar), OBSERVE (filled bar, lined) and MOTOR (filled bar, crossed) groups. Foot angle (thin bar) and knee angle (thick bar) were obtained at pre-slip touchdown of the slipping limb. Foot angle was the angle between the foot segment and the horizontal. Knee angle was obtained as external angle between the thigh and shank at the same instant. The normalized IEMG was obtained by integrating the EMG activity of the subtracted rectified profile from touchdown of the slipping limb to 100 ms post-touchdown and dividing it with the integral of the ensemble average of the three normal walking trials over the same period. The rectified EMG signal of each slip trial was subtracted from that of the ensemble average of the three regular walking trials after time aligning them to touchdown of the slipping limb to obtain the subtracted profile. The values for comparisons for 0.001 < p < 0.05 are indicated. The level for comparisons with p > 0.05 has not been indicated.

Figure 5. Comparison of group means (+ 1 SD) of (a) base of support displacement (X_{BOS}) and velocity (\dot{X}_{BOS}), (b) impulse under the slipping limb, and “post-slip” integrated electromyography activity (IEMG) for (a) biceps femoris (BF) and (b) tibialis anterior (TA) for the NAÏVE (open bar), OBSERVE (filled bar, lined) and MOTOR (filled bar, crossed) groups. The base of support displacement and velocity were obtained at post-slip liftoff of the contralateral limb. The impulse under the slipping limb was obtained by integrating the ground reaction force recorded in the anterior-posterior
direction under the slipping limb from touchdown of the slipping limb to post-slip liftoff of the trailing limb. The normalized IEMG was obtained by integrating the EMG activity of the subtracted rectified profile over a 200 ms period from 100-300 ms post touchdown of the slipping limb and dividing it with the integral of the ensemble average of the three normal walking trials over the same period. The rectified EMG signal of each slip trial was subtracted from that of the ensemble average of the three regular walking trials after time aligning them to touchdown of the slipping limb to obtain the subtracted profile.
The values for comparisons for 0.001 < p < 0.05 are indicated. The level for comparisons with p > 0.05 has not been indicated.
Figure 1

a) Backward Loss of Balance

b) No Loss of Balance
Figure 2

NAÏVE group (1st slip)

- BF-R (V)
- TA-R (V)
- $V_{BOS}$ (m/s)
- $F_Z$ (N)

Time (S)

Figure 2
Figure 3

(a) Pre-slip Stability

(b) Post-slip Stability

Group: NAIVE, OBSERVE, MOTOR

p = 0.08

p < 0.001

p = 0.03

Figure 3
Figure 4

Group
NAIVE OBSERVE MOTOR

Angle (Degree)

Foot
Knee

Pre-slip BF (Normalized)

p < 0.001

p < 0.001
Figure 5

**a)**
- $p = 0.04$
- $p = 0.06$
- $p = 0.09$
- $p < 0.01$

**b)**
- Impulse (slipping limb) Ns
- NAIVE
- OBSERVE
- MOTOR
- $p = 0.10$
- $p = 0.06$

**c)**
- Post-slip BF (Normalized)
- $p < 0.01$

**d)**
- Post-slip TA (Normalized)
- $p < 0.01$
a) Backward Loss of Balance

b) No Loss of Balance

Figure 1
Figure 2

NAÏVE group (1st slip)

- BF-R (V)
- TA-R (V)
- $V_{BOS}$ (m/s)
- $F_Z$ (N)

Time (S)
Pre-slip Stability

Post-slip Stability

Figure 3
Figure 4

**a)** Group NAIVE OBSERVE MOTOR

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p < 0.001

**b)** Group NAIVE OBSERVE MOTOR

<table>
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p < 0.001
Figure 5