Strategies for Dynamic Stability During Locomotion on a Slippery Surface: Effects of Prior Experience and Knowledge

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INTRODUCTION

We are constantly faced with the challenge of traversing through different environmental conditions such as wet, icy, soft, and irregular terrain. A primary concern of the CNS is to maintain dynamic stability during locomotion on such surfaces. Dynamic stability during locomotion is the control of the center of mass (CoM) within a changing base of support and requires effective proactive and reactive recovery response strategies when exposed to perturbations (Patla 1996). Reactive strategies by definition are elicited following unexpected sensory information such as when stepping on a slippery surface; but it is realized that responses are influenced by prior experience with and knowledge about the surface characteristics. The effects of knowledge are evident when we compare our reaction to stepping on to an icy surface as in a skating rink (presumably we know about the surface characteristics) versus stepping on black ice in the path that we did not see. The effects of prior experience are evident when we compare subsequent steps on a skating rink surface to the initial steps. Stepping on and off a slippery surface is the paradigm used to explore these issues. While this is clearly of primary interest, it is also relevant for addressing the issue of falls due to slips in the elderly (Cham and Redfern 2001; Pai and Iqbal 1999; Tang and Woollacott 1998).

The ability of the CNS to adapt to changing balance constraints is fundamental in maintaining an upright posture during both stance and locomotion. Studies on the control of upright posture show that the CNS is able to accommodate different types of perturbations and support surface characteristics (Hansen et al. 1988; Horak and Nashner 1986; Mummel et al. 1998; Nashner 1982; Nashner et al. 1982). Early work on perturbing balance during locomotion in humans suggested that the recovery strategies are similar in organization to strategies used to maintain upright stance (Nashner and Forssberg 1986). Later work by Dietz et al. (1985, 1989) suggested that group II and III afferents were responsible for the triggering and organization of the recovery response. The CNS appears to control an unexpected slip with early muscle onset latencies from the perturbed leg, suggestive of polysynaptic spinal reflexes or supraspinal loops, with no discernible contributions of arm muscles in young individuals (Tang and Woollacott 1998, 1999; Tang et al. 1998). Furthermore, corrective responses to a slip appear to include a flexor knee moment and extensor hip moment (Cham and Redfern 2001). Key factors that distinguish between individuals who fall due to a slip and those that do not are increased displacement of the slipping foot (Brady et al. 2000) and shorter double support phase while on the slippery surface (You et al. 2001). These results suggest that recovery strategies from a slip are modifiable.

Research on the control of upright posture provides the richest source of the effects of prior knowledge and prior experience on balance control. This holds true despite the fact that it is difficult to clearly differentiate between the two since...
any instructions given to the individual about the timing and characteristics of the upcoming perturbation can be used to update their knowledge. Even if the perturbation is kept the same, information about when it is going to occur is needed if proactive strategies are to be exploited.

Previous exposure to the perturbation has been shown to influence the reactive response strategies: decreases in the magnitude of the postural response, a more cost efficient strategy, are consistently observed (Buchanan and Horak 1999; Corna et al. 1999; Hansen et al. 1988; Horak and Nashner 1986; Keshner et al. 1987; Mummel et al. 1998; Timmann and Horak 1997). Rand et al. (1998) have recently studied adaptive changes in cerebellar patients and normal controls in response to repeated treadmill perturbations during locomotion. Changes were noted in step length, anterior-posterior postural sway, and the duration and co-ordination of lower leg muscle activity (Rand et al. 1998). These responses adapted gradually over repeated exposures to the perturbation (Rand et al. 1998). Tang et al. (1998) report that the early proximal muscle activation in the initial slip trial during force platform translations tends to fade away in subsequent slip trials, although no details of comparison were provided in their paper.

Effects of prior knowledge on the recovery response can be studied when following repeated exposure to a particular type of perturbation the perturbation is altered. Early work by Nashner (1976) showed that the initial response to a sudden change in the type of perturbation (from platform moving back to the platform tilting up, both of which produce the same stretch in the calf muscles but require different recovery responses) was similar to what was seen for the prior perturbation and therefore clearly inappropriate. The inappropriate response was replaced by the correct one within three to five trials (Nashner 1976). In contrast, Hansen et al. (1988) and Timmann and Horak (1997) both found an excessively large (but appropriate) postural response when the type of perturbation changed followed by a large reduction in the subsequent trial. Habituation of a “startle-like” response has been used to explain this modification (Hansen et al. 1988; Timmann and Horak 1997). Studies on the effects of fear of falling also show clear evidence of cognitive influence on posture control (Brown and Frank 1997; Carpenter et al. 2001). These studies highlight the role of expectation (knowledge) on postural recovery responses. There are few studies on the effects of prior knowledge about surface characteristics on locomotion. When an oily patch (Cham and Redfern 2002a; Myung and Smith 1997) or a soap patch (You et al. 2001) that can be seen is used to provide a slippery surface, individuals have been shown to modify their response strategy.

Slips during locomotion have been studied using various means, including force platform translations (Pai and Iqbal 1999; Tang and Woollacott 1998, 1999; Tang et al., 1998), oil (Brady et al. 2000; Cham and Redfern 2001, 2002a; Myung and Smith 1997), or soap-and-water (Hansen et al. 1999)-covered vinyl, a soap patch (You et al. 2001), a soap-covered carpet (Hansen et al. 1999), and a set of low-friction rollers (Smeesters et al. 2001). While support surface translation perturbs balance and provides more control over the magnitude of the perturbation, it differs from a slip on low friction surfaces in two aspects. First, there is no displacement of the foot relative to the surface. Thus the perturbation is restricted to heel-contact phase in the forward direction and not during push-off action (unless specifically programmed to), which on a slippery surface results in a slip in the backward direction. And second, the response to the support surface translation cannot be adjusted based on a change in loading of the surface because the apparatus rather than the individual controls the slip. Specifically, with a low-friction surface (e.g., rollers) the perturbation is dependent on the foot-surface interaction rather than the magnitude of the perturbation under the manipulation of the experimenter as is the case with a moveable force platform.

In this study we used a custom-built surface that allowed us to alter it such that it either provided normal surface friction or a surface with minimal friction. Our goals were to characterize the time course of response adaptation when stepping on a slippery surface, to investigate the reactive recovery responses used to maintain dynamic stability, and to establish the proactive strategies for negotiating a slippery surface. By letting the individuals know that the surface will be slippery for a particular trial within a block and comparing it to when they had no prior knowledge, we were able to quantify the effects of prior knowledge about the surface characteristics on the recovery response. By examining the changes in recovery response strategies to repeated exposure to the slippery surface, we were able to chart the time course of response adaptation.

**METHODS**

Twelve (8 female and 4 male) healthy, young adults from the University of Waterloo participated in this experiment. The mean age, weight, and height of the participants were 20.67 ± 1.23 (SD) yr, 67.01 ± 6.43 (SD) kg, and 173.75 ± 9.45 (SD) cm, respectively. The University of Waterloo Ethics Committee reviewed and approved the study.

**Slip apparatus and protocol**

The induced slip was provided by a set of steel rollers that could be locked or unlocked. Contact with the rollers in the unlocked position caused them to rotate and thus provided a slip in the anterior-posterior (A-P) direction. The rollers (mass of 38.6 kg; roller diameter = 2.54 cm; static coefficient of friction (μs) = 0.04, dynamic coefficient of friction (μd) = 0.03) were mounted on a force plate and sat flush in the middle of a 6.5-m-long, 3.8-cm-elevated wooden walkway with crash mats along the sides (see Fig. 1). Participants made direct contact (via their shoe) on the rollers that were clearly visible at all times. The rollers themselves were not in contact with the force plate; rather, they were encased in a frame (and in ball bearings) with a steel plate on the bottom that provided the contact with the force plate. Thus the ground reaction forces were not affected by the rotation of the rollers. With no load, the rollers are free-wheeling, with resistance provided by the friction in the ball bearings. Participants wore a full-body harness with a rope attached at the back: the experimenter held the rope while walking off to the side and behind the participant to prevent any occurrence of a fall. In the case of a fall, the experimenter would be able to catch the participant via the rope and a spotter trailing behind could assist. The rope in no way interfered with the participants’ behavior/response during the walking task. Before data collection began, participants were given several practice trials to become familiar with the walkway and to determine the starting position and walking velocity necessary to correctly step with their right foot on the rollers and their left foot on the preceding force plate. During the practice trials, the rollers were always locked and the
participants were not aware that they could be unlocked. The starting position was adjusted (i.e., the participants were told to start either a few centimeters forward or backward than the previous trial) throughout the experiment to ensure correct foot placement on the rollers as participants became more comfortable with the walkway and task and altered their step length slightly. The participants were told to look straight ahead while walking.

Each participant was presented with 8 blocks of 10 trials (a total of 80 trials). In four blocks (a total of 40 trials), knowledge (YK) of the surface condition was provided (i.e., participants were told whether the rollers were unlocked or locked in each trial). In the other four blocks, no knowledge (NK) of the surface condition was given (i.e., participants were told nothing before starting to walk). Before each trial, participants faced away from the rollers to allow the experimenter to unlock, lock, or do nothing to the rollers. For both the NK and YK conditions, this procedure was performed to provide consistency to the protocol. The first block of 10 trials always consisted of NK trials with the rollers locked. In addition, the second block always consisted of NK trials; however, in two random trials within the block of 10, the rollers were unlocked and provided a slip perturbation. Participants were not provided knowledge of the rollers’ condition; thus the first slip trial represented a “truly unexpected slip” in that no prior experience of a slip on this particular surface was available to the individual. The third block consisted of 10 YK trials for each participant with two random slip trials. Blocks 4–7 were counterbalanced between participants, consisting of two NK blocks and two YK blocks, each with two random slip perturbations. The last block always consisted of YK trials with two random slip perturbation trials. A total of 18.75% of the trials induced a slip (refer to Table 1 for the order of the 1st 12 slip trials). Kinetic, kinematic, and EMG data were collected concurrently for each trial.

To determine the static coefficient of friction (COF) for the rollers, a 20-kg weight was pulled across the rollers a total of five times (see Fig. 1D). At the point just prior to movement of the weight, the ratio of $F_x$ (A-P force)/$F_y$ (vertical force) was determined for each trial and then averaged to give the static coefficient of friction (see Fig. 1B). For the dynamic COF, the ratio of $F_x/F_y$ was determined during the weight sliding across the rollers.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Order of Slip Trials</th>
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<tbody>
<tr>
<td>1 and 7</td>
<td>2 NK, 4 YK, 4 NK, 2 YK</td>
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<tr>
<td>2 and 8</td>
<td>2 NK, 6 YK, 4 NK</td>
</tr>
<tr>
<td>3 and 9</td>
<td>2 NK, 2 YK, 2 NK, 4 YK, 2 NK</td>
</tr>
<tr>
<td>4 and 10</td>
<td>2 NK, 2 YK, 2 NK, 2 YK, 2 NK, 2 YK</td>
</tr>
<tr>
<td>5 and 11</td>
<td>2 NK, 4 YK, 2 NK, 2 YK, 2 NK</td>
</tr>
<tr>
<td>6 and 12</td>
<td>2 NK, 2 YK, 4 NK, 4 YK</td>
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</table>

FIG. 1. Experimental set-up. A: a bird’s eye view of the wooden walkway showing force plate position and rollers mounted on one. Also shown are camera positions. B: low-friction rollers used; $\mu_s$, static coefficient of friction for the rollers, $\mu_d$, dynamic coefficient of friction for the rollers. C: foot-surface interaction on the rollers during locomotion. D: set-up for determining the coefficient of friction of the rollers.

Table 1. Order of no knowledge (NK) and knowledge (YK) slip trials
EMG data collection and analysis

Four pairs of bipolar surface electromyographic (EMG) electrodes were used to record the activity of rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and the medial head of gastrocnemius (MG) on the perturbed limb (limb that made contact with the rollers). All raw EMG analog signals were sampled at 1,200 Hz for 6 s. For analysis, the raw EMG signals were full-wave rectified and low-pass filtered at 10 Hz (using a 2nd-order Butterworth algorithm) with a custom-written program. Foot contact (FC) with the rollers was determined using a separate program and used to clip the data 2 s before and after the FC frame. Each muscle response profile for a slip trial was determined by subtracting the ensemble average profile of the control trials from the slip trial. The control trials used were the relevant unperturbed trials in each block of the corresponding slip trial. For the first slip, the control trials were taken from the first block of trials. Subsequently, the onset, offset, and duration of each muscle burst was calculated for two seconds following FC with the rollers using a custom program. The existence of a recovery muscle response burst was defined as an increase in muscle activity that exceeded +2 SD (for an excitatory burst) or fell below −2 SD (for an inhibitory burst) for ≥30 ms. The burst duration was defined from onset to when the muscle activity fell below +2 SD (for an excitatory burst) and exceeded −2SD (for an inhibitory burst) for a minimum of 30 ms.

For each slip trial in all conditions, the muscle activity (i.e., area under the muscle response curve) was determined between 120 and 200 ms. This time frame was chosen since the muscle onset latencies were within this period.

Kinematic and kinetic data collection and analysis

Ground reaction forces were sampled at 1,200 Hz using two AMTI force plates along with the EMG data during collection and subsequently processed using a custom written program. The FC and toe-off events on the rollers and preceding force plate were determined if the vertical force (Fy) exceeded or fell below a 15 N threshold. A summary of the kinetic and kinematic variables is shown in Table 2. The zero transition from negative to positive values of the Fx (A-P force) for the force plate was used to differentiate between the braking (Fx)/loading (Fy) and accelerating (Fx)/unloading (Fy) phase of the rollers. Six kinetic measures were determined and used for later analysis including braking impulse, accelerating impulse, loading impulse, unloading impulse, rate of loading (RoL), and rate of unloading (RoUL). All measures were adjusted for body weight. The braking impulse (Ns/kg) represented the area under the A-P force curve from FC on the rollers to the zero transition while the accelerating impulse (Ns/kg) represented the area under the zero transition to toe-off on the rollers. The loading impulse (Ns/kg) represented the area under the vertical force curve from FC on the rollers to the zero transition, whereas the unloading impulse (Ns/kg) represented the area under the vertical force curve from the zero transition to toe-off on the rollers. The RoUL (Ns/kg) represented the slope of the vertical force curve (from the force plate with the mounted rollers) during the first double support phase, whereas the RoUL (Ns/kg) represented the slope of the vertical force curve (from the force plate preceding the rollers) during the first double support phase.

Three OPTOTRAK three-dimensional (3D) camera systems (Northern Digital) were used to collect whole body kinematic data. A total of 23 infrared emitting diodes (IREDs) were placed bilaterally on the heel, fifth metatarsal bone, frontally at the level of the lateral malleolus, knee, greater trochanter, anterior superior iliac spine, iliac crest, acromion, lateral epicondyle of the humerus, styloid process of the radius, ear, and the xyphoid process of each participant. The cameras’ sampled the IREDs at 60 Hz for 6 s with the kinetic and EMG data. A video camera (Panasonic) recorded the slip from the right side for qualitative observations. The 3D position data for all IRED markers were low-pass filtered at 10 Hz (using a 2nd-order Butterworth algorithm). A custom program then determined the total body CoM in the x, y, and z directions and selective kinematic measures including foot angle and foot excursion during the stance phase on the rollers. Due to the frequent use of an arm elevation strategy during slips, the IREDs positioned on the arms were blocked from the view of the cameras at critical time periods and thus the CoM without the forearm/hand and arm segments was determined and used for subsequent analysis. An eight-linked-segment model was used for calculating the CoM, where the anthropometric data compiled by Winter (1990) was used (see Table 3 for details on segment definitions and information). Furthermore, the formula for estimating the CoM was the weighted sum of the CoM of every segment

\[
\text{CoM} = m_1 \alpha_1 + m_2 \alpha_2 + \ldots + m_n \alpha_n
\]

where \( \alpha \) is the x, y, or z direction coordinate of the CoM of the segment and \( m \) is the mass of the segment. The foot angle represented the angle between the ground and the line joining the heel and fifth metatarsal markers (see Fig. 7A) for the perturbed limb (i.e., right). These two kinematic measures were determined from FC on the force plate prior to the rollers and the following FC after the rollers by the same limb (i.e., left), where FC by the perturbed limb (i.e., right) occurred in between these events. The peak foot angle prior to contact with the rollers (which occurred within 10 ms from contact) and peak vertical CoM following contact with the rollers (i.e., 1st peak in the profile) were used for later analysis. The foot excursion during the stance phase on the rollers in the plane of progression was determined by calculating the displacement of the heel marker from FC to toe-off on the rollers (see Fig. 8B). Medial-lateral (M-L) displacement stability margin was also determined (Perry et al. 2001). This margin represented the minimum distance between the CoM and the borders of the base of support. A line running perpendicular to the M-L heel position (i.e., line through the center of the foot) at the time of FC on the rollers determined the edge of the base of support (see Fig. 9A).

The kinematic profiles of both the endpoints of the two arms and the swing limb for the horizontal and vertical directions for the first slip were analyzed to describe some of the strategies used to recover balance after the perturbation. This included determining the onset of

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**TABLE 2. Summary of the definitions of the kinetic and kinematic variables**

<table>
<thead>
<tr>
<th>Variable/Abbreviation</th>
<th>Definition</th>
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<tr>
<td>Foot angle</td>
<td>Angle between a line joining the heel and the fifth metatarsal marker and the ground for the perturbed limb</td>
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<tr>
<td>Center of mass (CoM)</td>
<td>Peak vertical center of mass following FC on the rollers</td>
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<tr>
<td>Stability margin</td>
<td>The minimum distance between the CoM and a line running through the center of the foot perpendicular to the heel marker</td>
</tr>
<tr>
<td>Rate of loading (RoL)</td>
<td>The slope of the vertical force curve (from the force plate with the rollers) during the first double support phase</td>
</tr>
<tr>
<td>Rate of unloading (RoUL)</td>
<td>The slope of the vertical force curve (from the force plate with preceding the rollers) during the first double support phase</td>
</tr>
<tr>
<td>Braking impulse (BI)</td>
<td>Area under the A-P force curve from FC on the rollers to the zero transition</td>
</tr>
<tr>
<td>Accelerating impulse (AI)</td>
<td>Area under the A-P force curve from the zero transition to toe-off on the rollers</td>
</tr>
<tr>
<td>Loading impulse (LI)</td>
<td>Area under the vertical force curve from FC on the rollers to the zero transition</td>
</tr>
<tr>
<td>Unloading impulse (UnLI)</td>
<td>Area under the vertical force curve from the zero transition to toe-off on the rollers</td>
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a change from the control ensemble profiles and the direction of change in the displacement profiles.

Statistical analysis

A one-way (muscle) repeated-measures ANOVA (RM ANOVA) on muscle onset latency was performed for the first slip trial. The data were tested for normality and was rank transformed. Post hoc analysis consisted of the least-squares means test, as there were unequal observations due to missing data between comparisons. A one-way (trial) RM ANOVA using the first and subsequent five NK slips (n = 6, NK slips) for each participant was performed to determine whether a trial effect existed and if so, to determine the time for adaptation to occur. This procedure was performed for each kinetic and kinematic variable. Furthermore, the muscle activity (i.e., the area under the response curve) for each muscle from 120 to 200 ms after FC on the rollers was used for the analysis considering each muscle separately. The time interval of 120–200 ms was used because the onset latency observed for the first slip occurred during this period. These procedures were performed for the YK slips (4 trials taken from the counterbalanced blocks) as well. Post hoc analysis used the Bonferroni t-test with an alpha level of 0.05.

A total of 5 trials (where the participants showed correct foot placement and no data were missing due to equipment problems) prior to the first slip were used as “true” control trials for analysis. A dependent t-test was performed for the kinetic and kinematic data comparing the first slip with the “true” control trials to aid in explaining the recovery response. Four participants slid on the rollers with both feet for the first slip. For all impulse measurements, these four participants were removed because this strategy would greatly affect the forces applied to the rollers. Four trials with knowledge provided and the rollers locked were used as the YK controls. These trials were chosen from the counterbalanced blocks, where two trials were randomly chosen from each of the two YK blocks. Conversely, four trials without knowledge provided and the rollers locked were used as the NK controls. These trials were chosen from the counterbalanced blocks as well, where two trials were randomly chosen from each of the two NK blocks. Because there were no trial effects for control trials within the same block (data not reported), it was assumed that these randomly chosen control trials adequately represented normal, unperturbed walking for comparison. Statistical analysis consisting of a one-way RM ANOVA was performed on the three sets of control group trials to discover whether participants were healthy young adults. In addition, the fact that the rollers were clearly visible in the travel path may have influenced the participants gait from the onset of the experiment. Behavioral responses to slips when the slippery surface blends with the environment and is not visibly obvious would be different.

First slip-recovery response

The first slip response was clearly different from the subsequent slips. The typical recovery response profiles exhibited by RF, BF, TA, and MG for the first slip are shown in Fig. 2A. The figure illustrates the sequence of long latency reflexes in the recovery response. The four muscles showed a significant difference in onset latency (Fig. 2B) in response to the first slip trial [F(3, 33) = 4.38, P = 0.0106]. Post hoc analysis using the least-squares means test revealed that TA (145.97 ± 13.8 ms) and BF (153.54 ± 30.2 ms) were activated together followed by RF (174.65 ± 32.7 ms) and MG (199.23 ± 95.9 ms) together. Using a Bonferroni correction, data points were removed to show that MG was activated with BF and TA. Because there is no a priori functional reason for eliminating data points, we chose the former method for discussion.

The first slip recovery response was determined by comparing the first slip to the normal, unperturbed, walking trials. The mean values for each kinematic and kinetic variable comparing the first slip with its corresponding control trials are shown in Table 4. The vertical CoM (no arms) for the first slip was significantly reduced suggesting a more stable position to recover balance. The RoL was also significantly reduced for the first slip. This may indicate a strategy whereby the CoM has been positioned over the contralateral limb for a longer period. Once the participants realized their balance was compromised from the slip perturbation, they attempted to ensure a safe forward progression off the rollers. This is reflected in the significantly reduced accelerating impulse and unloading impulse during the first slip.

Effects of prior experience: response adaptation

In slip trials where knowledge was provided, no adaptation was seen. However, adaptation of the recovery response was demonstrated over repeated exposures to an unexpected slip perturbation. This adaptation occurred within one slip trial. Three of the four muscles measured showed significant trial effects (see Fig. 3) in the NK slip trials for muscle response
magnitude between 120 and 200 ms after FC on the rollers including BF \[F(5,54) = 5.87, P = 0.0002\], TA \[F(5,54) = 5.90, P = 0.0002\], and MG \[F(5,54) = 7.35, P = 0.0001\]. Both BF and TA showed a large excitatory response for the first slip while the response was significantly attenuated in the remaining slips \((P < 0.05)\). However, a different trend was seen for MG. There was an excitatory response for MG in the first slip; however, in the remaining slips the response became inhibitory. The onset latencies for slips after the initial slip were not determined because they were too difficult to isolate due to proactive muscle activations. The adaptive change was not isolated to muscular responses. Typical force profiles comparing an unperturbed walking trial prior to the first slip with the first slip trial and another NK slip trial are shown in Fig. 4 (A and B). The braking impulse also demonstrated a trial effect (see Fig. 4C) with a large braking impulse for the first slip and a subsequent decrease in the remaining slip trials \[F(5,45) = 11.54, P = 0.0001\]. There was a trend for the acceleration impulse to gradually increase (Fig. 4D) with repeated exposures to the perturbation. Furthermore, both vertical CoM and foot angle at FC showed a trial effect (see Fig. 5). A
large foot angle at FC was seen in the first slip, which was reduced in the remaining slip trials $[F(5,54) = 8.20, P = 0.0001]$. On the other hand, the vertical CoM was elevated following the first slip $[F(5,52) = 20.13, P = 0.0001]$. Arm elevation and swing limb strategies

All participants demonstrated an arm elevation strategy as a recovery mechanism for the first slip trial. The mean onset time for a change in arm trajectory in the vertical direction for the right and left arms was 298.61 ± 53.4 and 288.89 ± 42.8 ms, respectively. The onset time for the horizontal direction for the right and left arms was 331.48 ± 100.5 and 297.22 ± 95.8 ms, respectively. There was a rapid increase in velocity to elevate both the arms up and forward simultaneously to maintain balance (see Fig. 8A, top). The swing limb showed a decrease in velocity with a change in trajectory occurring 205.56 ± 61.3 ms in the vertical direction and 358.33 ± 52.5 ms in the horizontal direction after FC with the lead limb on the rollers. Four of the 12 participants rapidly lowered their swing limb and slid on the rollers with both feet for the first slip. Four additional participants displayed a toe-touch response (i.e., swing limb toe made contact with the walkway beside the rollers for a brief moment before continuing with the normal swing trajectory). Lowering of the swing limb to make contact with the ground, albeit briefly, provides a larger base of support, momentarily increases stability and increases the likelihood of recovery. Following the first slip, this swing limb response vanished: presumably the adaptation established played a role in this observation. Although an arm elevation strategy was observed for most slips, the response was drastically reduced compared with the first slip response. Thus this strategy (along with the swing limb response) was considered for the first slip only.

Effects of knowledge on the recovery response: proactive strategies

Knowledge of the impending surface characteristics led to gait modifications to safely traverse the potentially unstable surface. After experiencing the slip and realizing the possibility of a second one existed, individuals clearly adjust their gait to adopt a cautious strategy.

Normal gait patterns also showed changes: the comparison was among the unperturbed trials before the first slip, after the first slip with no knowledge provided, and after the first slip when knowledge was provided. Several measures show a significant main effect including foot angle $[F(2,22) = 23.13, P = 0.0001]$, vertical CoM $[F(2,22) = 25.17, P = 0.0001]$, braking impulse $[F(2,20) = 31.16, P = 0.0001]$, loading impulse $[F(2,20) = 22.23, P = 0.0001]$, and RoL $[F(2,20) = 12.84, P = 0.0003]$. Post hoc analysis uncovered that for each measure, the “true” control trials were significantly different from normal unperturbed walking.
the NK controls and that the NK controls were significantly different from the YK controls.

Typical force profiles for the NK and YK unperturbed and perturbed trials are illustrated in Fig. 6 (A and B). The shear forces measured during the experiment are larger than what would be expected given the measured static and dynamic COF. The difference can be explained by the nature of the foot-surface interaction seen during the experiment that is clearly different from the application of forces during COF measurement (see Fig. 1, C and D). During measurement of COF, the contact between the weight and the rollers is ideal: point contact at every instant and loading normal to the surface (see Fig. 1D). In contrast, the sole of the shoe deforms as the person makes contact with the rollers; this deformation between the rollers produces higher shear forces during the weight transfer phase in early stance. During late stance when the foot is beginning to be unloaded, the deformation of the sole of the shoe may not be as dramatic and hence the shear forces are considerably smaller (see Fig. 4A). Braking impulse \([F(1,10) = 10.31, P = 0.0093]\), RoL \([F(1,10) = 21.74, P = 0.0009]\), and loading impulse \([F(1,10) = 14.43, P = 0.0035]\) showed a significant knowledge (no vs. yes) by slip (no vs. yes) interaction (see Fig. 6, C–E). Post hoc analysis revealed that the braking impulse was significantly reduced during the YK slip and NK no slip trials compared with the YK no slip trials. Thus when the possibility of a slip existed, individuals chose to be cautious and reduce braking on the rollers. In addition, the RoL was significantly reduced when knowledge of an impending slip was provided compared with when no slip was imminent. A similar significant reduction was observed for the NK no slip trials compared with the YK no slip trials. A decrease in the RoL suggests the center of pressure was allowed to remain closer to the contralateral limb base of support, which would serve to reduce the amount of braking force applied to the rollers as was shown. Significant differences in loading impulse showed that loading was increased in the slip trials both with and without knowledge provided. Furthermore, a cautious strategy was employed as seen with a significantly reduced amount of loading in the NK no slip trials compared with the YK no slip trials. Changing how one steps onto a surface can affect (and effect) both braking and loading forces. Foot angle at FC showed a significant interaction \([F(1,11) = 97.97, P = 0.0001]\) as seen in Fig. 7B. When knowledge was given, there was a significant decrease in foot angle at FC. When knowledge was not provided, foot angle at FC was significantly reduced compared with the YK no slip trials and represents a more cautious strategy when unsure of the upcoming surface conditions. The decreased foot angle relative to the ground indicates a strategy whereby the individual steps more flat footed on the rollers and thus acts to facilitate a reduction.

**Fig. 4.** Typical NK condition force profiles for 1 participant (2) and impulse adaptation to repeated unexpected slip perturbations. A: anterior-posterior (A-P) force from 1 control trial, the 1st slip, and 1 no knowledge (NK) slip trial during contact with the rollers. B: vertical force from 1 control trial, the 1st slip, and 1 NK slip trial during contact with the rollers. C: braking impulse adaptation from repeated unexpected slip perturbations. D: accelerating impulse adaptation from repeated unexpected slip perturbations. Error bars represent SE.
The novelty of the first slip provided a means to assess the reactive postural responses to a slip perturbation. The mean muscle onset latencies (range, 146–199 ms) during the first slip suggest the contribution of polysynaptic reflexes to recover balance following an unexpected slip. Consistently, the earliest dominant recovery response is observed at long latencies ranging from 70 to 140 ms in several studies where perturbations to balance were induced during locomotion (Berger et al. 1984; Cham and Redfern 2002b).
Eng et al. 1994; Tang and Woollacott 1998, 1999; Tang et al. 1998). The onset latencies in this study suggest that proprioceptive cues are responsible for the triggering of the recovery response. The visual system requires more time to initiate a response, and the vestibular system relies on head movement to perturbations, which would be dampened by the inherent viscosity of tissues between the feet and the head. The reactive recovery response organization showed that BF and TA were activated first followed by MG and RF. This sequencing differs in the response organization compared with the study by Tang et al. (1998) in which they showed a clear distal to proximal sequence. The difference may be explained by the fact that in the Tang et al. (1998) study all slip trials were used, whereas in the present study only the first slip trial was used in the muscle onset calculations and the first slip was shown to differ considerably from subsequent slips. In the present study, the organization of the muscle response may represent a flexor synergy and serve several functions. Early activation of TA and BF serve to flex the ankle and the knee joint, respectively, which should result in lowering of the body toward the base of support. Cham and Redfern (2001) have recently showed that a knee flexor moment is produced as part of the recovery response to a slip perturbation. The lowering of the body is clearly seen in the CoM (Table 4) and represents a strategy to improve stability. If the swing trajectory is not modified, this lowering of the whole body will lead to early termination of the swing phase as seen in eight participants: early onset of double support phase also serves to improve stability by increasing the base of support.

As a consequence of the induced slip and early activation of
BF (which serves to extend the hip joint), the trunk, and hence CoM, falls backward. The observed arm elevation strategy serves to counteract this event and help stabilize the CoM by shifting it more anteriorly. It has been recently shown that reaction force and moments generated by arm movements can be used to passively control the overall CoM during standing (Patla et al. 2000). Muscle activity responsible for the arm movement change has to precede a change in kinematics. Judging by the onset time for the arm movement change, this response would occur at about the same time as the lower limb muscle response (taking into account the electromechanical delay and musculo-skeletal dynamics). Therefore the arm movements represented an integral part of the early recovery response to the novel, unexpected slip. Individuals did in fact exhibit a large and rapid arm elevation strategy in response to the first slip perturbation. You et al. (2001; inferred from sample postural diagram in paper) also found a similar arm elevation strategy for individuals who recovered from a slip. In contrast, Tang and Woollacott (1998) found few young adults used an arm elevation strategy whereas this response was frequently seen in older adults. This difference could possibly be due to a larger perturbation induced by the rollers (very low friction).

In terms of changes in loading the slippery surface, the first slip saw a decrease in RoL, the acceleration impulse, and the unloading impulse compared with unperturbed control trials. To ensure safe forward progression, the control of push-off phase on a slippery surface is critical. The decrease in acceleration impulse (i.e., A-P force) and unloading impulse (i.e., vertical force) is consistent with the notion that a large propulsive force on a slippery surface would further increase the risk of a fall. This is also consistent with Patla et al. (1993), who reported individuals tend to pull up rather than push off a compliant surface. The decrease in RoL occurs during the first double support phase while in contact with the rollers and thus suggests that the sensory input during this brief time period is sufficient to adjust the individual’s gait and subsequent loading. Recently Perry et al. (2001) showed similar changes when the plantar surface of the foot was cooled. This suggests that cutaneous input from the feet may be responsible for the rapid response in the RoL.

Adaptation from repeated exposures to slip perturbations occurs rapidly

The CNS clearly adapts recovery responses to perturbations applied during locomotion. This adaptation is based largely on prior experience with the perturbation characteristics. The results of this study indicate a total body adaptation as seen with changes in muscle activity, kinematics, and kinetics. The adaptation was determined by comparing the six NK slip trials for each participant even though different participants experienced a different number of YK slip trials between the NK slip trials. However, we observed the adaptation to occur within one slip trial and the second slip trial for each participant occurred within the same NK block as the first slip. As a result, everyone had experienced the same amount of slips at this point. The most visually noticeable change was that the early arm elevation strategy seen in the first slip attenuated dramatically in the second slip trial. In subsequent trials, no appreciable arm movements were seen. In part, the reduction in arm movements is consistent with reduction in the response in BF, the cause of backward displacement of the trunk. Large muscle response magnitudes are seen with TA, BF, and MG for the first slip. These postural response magnitudes are immediately reduced in the subsequent NK slips. The muscle response magnitudes were not altered just prior to foot contact on the rollers, indicating that individuals did not adjust the way they walked prior to the rollers. However, it must be understood that after the first slip, individuals are aware of the perturbation threat, and in the NK trials, a cautious strategy was seen. Such a strategy has also been observed in a recent study where participants anticipated a slippery surface (Cham and Redfern 2002a). Furthermore, only in the first slip do we actually observe a purely reactive response. The facts that RF was not significantly altered during the time the responses were sampled (i.e., 120–200 ms) and the magnitude was small may suggest that this muscle does not play an important role in the early recovery response. Tang et al. (1998) argue that the RF is critical for recovery because it is involved in preventing knee collapse caused by the induced slip. Had the onset of RF been earlier than the observed 175 ms, the response magnitude may have been altered during the time period analyzed. The reduction in TA and BF activity in subsequent trials leads to concomitant changes in vertical displacement of the CoM: CoM is not lowered as much (see Fig. 5B). Interestingly, the excitatory response of MG in the first slip becomes inhibitory (i.e., sign change) in subsequent ones. This effective adjustment allows TA to sufficiently dorsiflex the foot and prevents further unnecessary plantarflexion induced by the slip. A similar coordination of these two muscles has been shown in response to slips induced by a moveable force plate (Tang et al. 1998).

The rapid adaptation between the first and second trial has in
the past, for stance perturbations, been attributed to the habituation of a startle-like response (Hansen et al. 1988; Timmann and Horak 1997). A startle response is more stereotyped and is characterized by a predominantly flexor response of the limbs, substantial co-contraction (Nieuwenhuijzen et al. 2000) and short muscle onset latencies (Hansen et al. 1988): the response seen here does not quite match these characteristics. For example, our response consisted of longer onset latencies (146–199 ms) compared with Hansen et al. (1988) at 90 ms. Whereas habituation is generally considered a gradual attenuation in

FIG. 8. A: typical stick figures of body posture during the 1st slip trial, a NK slip trial, a YK slip trial, and a NK no slip trial. The dark thicker lines represent the right side of the body (i.e., the limb that was perturbed), and the markers that constitute the line are shown for the 1st slip trial. The light thin lines represent the left side of the body. The time interval between consecutive stick figures is equal to 67 ms. B: a close-up defining the foot excursion for the YK slip trial with the ankle, heel, and 5th metatarsal markers shown. TO, toe-off on rollers. C: mean foot excursion on the rollers showing an interaction between knowledge and the presence of a slip. Error bars represent SE.
response magnitude to repeated exposures of the same perturbation (Timmann and Horak 1997), adaptation refers more to the ability of a system to alter its response such that the perturbation itself may be altered. In our study, although the perturbation is generated by the rollers for each slip trial, the perturbation itself is more a result of the foot-surface interaction and subsequently, each slip perturbation is not exactly the same. Although foot excursions did not significantly change over repeated trials, adjustments in the kinetic measures were seen. The adaptation made by the CNS provides the body with greater dynamic stability because it also serves to reduce the perturbation magnitude. Consequently, a small part of the altered recovery responses may be attributed to a slightly smaller perturbation size and not exclusively due to a neural factor. With previous studies, the moveable platform provides an identical perturbation, and thus the term habituation is appropriate to describe the observed reduction in response to repeated exposures. However, in the present study, an adaptation occurs, although one could argue that it is also habituation. Hansen et al. (1988) report that following the habituation of the startle-like response there was a continued gradual reduction in the response to repeated exposures of the perturbation. Several studies demonstrate the ability of the CNS to adapt rather quickly to repeated exposures of the same type of perturbation (Buchanan and Horak 1999; Keshner et al. 1987; Mummel et al. 1998; Nashner 1976). Nashner (1976) found the adaptation to occur within three to five sequential trials of the same perturbation. Horak and Nashner (1986) reported that there was a gradual shift in response strategy (ankle to hip or vice versa) to the more appropriate one following repeated exposures to support surface perturbations. Buchanan and Horak (1999) demonstrated decreases in center of pressure amplitude from trials one through to three in response to repeated exposures to fast frequency support surface translations. Studies describing adaptations during gait perturbations are limited. However, adaptation appears to also occur rather quickly (Rand et al. 1998).

The significant decrease in foot angle following the first slip suggests that the individuals were landing with a more flat foot. There are two ways of minimizing the chance of a slip at foot contact: reduce the contact velocity and/or increase the contact area. Brady et al. (2000) also showed similar changes in foot orientation at contact, although their measure was indirectly related to foot angle. Flat-foot landing provides increased contact area at landing and therefore represents an excellent adaptive strategy. In addition, flat-foot landing affords the individual the ability to maintain the elevation of the CoM as observed and also reduces the braking impulse.

**Knowledge of surface conditions can influence the choice of recovery response characteristics**

Prior knowledge seems to play a significant role in recovery responses to perturbations during locomotion. Knowledge of the surface condition provided the opportunity to proactively plan both the landing on the slippery surface and also modify the subsequent response.

First we will discuss the proactive changes made based on prior knowledge. These are changes to how the individual makes foot contact with the slippery surface. Gait patterns during normal unperturbed walking are modified based on prior experience. As shown with the changes between control trials, individuals clearly adopt a more cautious strategy. When they are aware of the surface characteristics, individuals modify their foot angle (Fig. 7B) and their stability margin (Fig. 9B). As seen, they land with a more flat foot, which increases the foot contact area, and they keep the CoM closer to the contralateral limb, which is in contact with the stable surface. A recent study by Cham and Redfern (2002a) suggests that the potential for a slip and/or a fall is attenuated by reducing the required coefficient of friction (RCOF) between the shoe/floor.

![Diagram](image-url)

**Fig. 9.** Medial-lateral (M-L) displacement stability margin interaction. With knowledge of the surface condition provided (YK) and without (NK). A: the stability margin represents the distance between the M-L CoM and an imaginary line perpendicular to the heel marker of the right foot at heel contact on the rollers. B: mean stability margin for each condition. Error bars represent SE.

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**Fig. 10.** Vertical CoM, with knowledge of the surface condition provided (YK) and without (NK). A: model used for CoM calculations (markers used are shown). Note that the arms were not included as part of the model. B: mean peak vertical CoM values for each condition. Error bars represent SE.
interface and that this is accomplished, in part, by a smaller foot angle. Thus the decreased foot angle seen in the present study when individuals were told they would slip (i.e., YK slip trials) may serve a similar function. Altering the position of the CoM to improve stability is similar to findings in posture studies when you expect a push from behind and you lean backwards (Brown and Frank 1997). Recently, Rietdyk and Patla (1998) have shown that individuals bias their CoM toward the support limb in the M-L direction as an anticipatory change to the possibility of being tripped. As long as the forward velocity of the CoM with respect to the base of support is sufficient, individuals are less likely to fall (You et al. 2001). Both changes serve to increase stability: changes to foot orientation minimizing chances of slipping and stability margin changes act as insurance should balance be threatened. Increasing the awareness of the stability boundaries of the base of support can facilitate recovery to platform perturbations (Maki et al. 1999).

Next we turn our attention to the strategies once individuals have stepped on the slippery surface. Individuals adopt a surfing strategy when they are aware that the surface is going to be slippery. This strategy consisted of holding the arms forward and outward slightly while the swing limb delayed landing and the perturbed limb slid on the rollers rather than attempting to step off quickly. The Fig. 8A, top, shows that for the first slip, there is a large foot excursion that increases the risk of falling. Note that the increased foot excursion results from the foot sliding on the rollers rather than from foot rotation about the metatarsal region (see Fig. 8A, top). The subsequent panels show that in the other conditions, foot excursion is decreased. The interaction graph in Fig. 8C shows that when individuals are unaware of an impending slip, they decrease the foot excursion in an attempt to step off the slippery surface more quickly. However, when individuals have knowledge of the surface condition, they maintain the same foot excursion (more translation, less rotation) and traverse the slippery surface in a more stable position. A similar strategy to the described surfing strategy has been demonstrated in response to slow sinusoidal support surface translation frequencies during stance (Buchanan and Horak 1999, 2001; Corna et al. 1999). Buchanan and Horak (1999, 2001) explain a “ride” pattern, which consists of minimal motion, if any, about the ankle, knee, and hip joints while being perturbed. The surfing strategy can be seen when people walk on a skating rink in street shoes. The pattern of taking a few short steps, then sliding (or surfing) on the ice followed by a few more short steps emerges. Surfing the rollers may inherently reduce the degrees of freedom the CNS must control to maintain balance (Buchanan and Horak 2001). Other changes on the altered surface include a decrease in braking impulse, reduction in rate of loading, and a lowering of the CoM. These changes are made possible because of the proactive changes implemented. In other words, when knowledge is provided the reactive responses are clearly influenced by the proactive strategies employed by the individuals. Better stability at landing allows the individuals to control their CoM deceleration. When the slip is unexpected, CoM is lowered thereby increasing stability because the mass of the body is closer to the base of support. However, when information is available, the CNS makes other changes to ensure that whole body CoM is not disturbed. Reduction in RoL ensures that acceleration of the CoM is unaffected. Thus as suggested by You et al. (2001), it appears as though the first double support phase is critical for recovery from a slip.

Conclusion

The CNS uses relatively fast onset latency muscle responses in a coordinated fashion to recover balance and maintain dynamic stability following a truly unexpected slip perturbation. Integrated into this reactive strategy is an essential arm response. Following the initial slip perturbation, the recovery responses are colored with the nervous system’s memory of past perturbations; subsequently, the plasticity of the CNS allows the coordinated motor programs that ensure safe progression to adapt and reduce the disturbing effects of a later slip.

The rapid recovery response adaptation to perturbations during locomotion is of profound importance because the destabilizing effects created by irregularities in terrain and surface characteristics stand to cause far greater debilitating effects compared with stance disturbances. The immediate adaptation in this study was evident from decreasing muscle response magnitude as well as decreasing braking impulse, foot angle, and elevating CoM with repeated perturbations.

Overall, the strategies demonstrated confirm that stability considerations are paramount. Examples of strategies emphasizing stability include, early swing limb contact in the first slip; increasing the M-L stability displacement margin, reducing foot angle, and reducing the rate of loading with knowledge of the surface conditions; and lowering the vertical CoM in response to a slip without knowledge of the surface conditions. These strategies clearly show the influence of cognitive factors (such as prior knowledge of the surface condition) on the recovery response and provide a framework for potential rehabilitation techniques for teaching individuals at risk of falling how to better adapt to slippery surface conditions and adequately maintain dynamic stability.

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REFERENCES


RECOVERY RESPONSES FROM A SLIP DURING LOCOMOTION


