Role of the Unperturbed Limb and Arms in the Reactive Recovery Response to an Unexpected Slip During Locomotion

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Understanding reactive recovery responses to slipping is fundamental in falls research and prevention. The primary purpose of this study was to investigate the role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip. Ten healthy, young adults participated in this experiment in which an unexpected slip was induced by a set of steel free-wheeling rollers. Surface electromyography (EMG) data were collected from the unperturbed limb (i.e., the swing limb) rectus femoris, biceps femoris, tibialis anterior, and the medial head of gastrocnemius, and bilateral gluteus medius, erector spinae, and deltoids. Kinematic data were also collected by an optical imaging system to monitor limb trajectories. The first slip response was significantly different from the subsequent recovery responses to the unexpected slips, with an identifiable reactive recovery response and no proactive changes in EMG patterns. The muscles of the unperturbed limb, upper body, and arms were recruited at the same latency as those previously found for the perturbed limb. The arm elevation strategies assisted in shifting the center of mass forward and broadening the perturbed base of support and to increase stability. Evidently a dynamic multi-limb coordinated strategy is employed by the CNS to control and coordinate the upper and lower limbs in reactive recovery responses to unexpected slips during locomotion.

INTRODUCTION

Reactive recovery responses are crucial in maintaining dynamic stability following an unexpected destabilizing event such as a slip and thus it is important to understand the nature of these responses. Falls resulting from inappropriate recovery responses to destabilizing events are of special concern in older individuals and are the subject of much research (Cham and Redfern 2001; Pai and Iqbal 1999). Recent studies on slipping have highlighted two important aspects of the early component of the recovery response. First, identifiable reactive responses are only seen in the first exposure to the destabilizing event; subsequent responses to perturbations are heavily influenced by proactive adjustments based on prior exposure (Marigold and Patla 2002). Second, studies have shown rapid responses (muscle activation within 90–200 ms) in the limb in contact with a slippery surface (Marigold and Patla 2002; Tang et al. 1998; Tang and Woollacott 1998, 1999).

Little is known about the role of the unperturbed limb (i.e., the swing limb) and the arms in the recovery response to an unexpected slip. It is fundamental to understanding reactive recovery responses to slipping that every aspect of body motion that can contribute to recovery is considered. Predominantly, research has focused on the perturbed (or slipping) limb (Brady et al. 2000; Cham and Redfern 2001, 2002a,b; Marigold and Patla 2002). The importance of the unperturbed limb is reflected in the recent finding that the critical time for regaining stability following the onset of a slip is during the first double support phase (i.e., when the perturbed limb is in contact with the slippery surface and the unperturbed limb is in contact with the ground behind this limb) of the gait cycle (You et al. 2001). During this phase the unperturbed limb is unloading from stable ground and about to begin swing phase. Consequently, it is still able to provide some form of stability prior to toe-off and is subsequently responsible for a rapid, stable landing to ensure dynamic stability throughout locomotion. Tang et al. (1998) showed that the unperturbed limb responds with rapid onset muscle activation (106–169 ms onset) and that interlimb coordination appears to be critical in the reactive recovery response to a slip. However, this study used a force platform translation to generate a slip. We have recently shown differences in muscle activation of the perturbed limb and in recovery responses using a set of steel rollers to provide a slip perturbation rather than a force platform translation (Marigold and Patla 2002). Whether the response of the unperturbed limb using a set of rollers is the same as shown in the study by Tang et al. (1998) remains to be seen. Our previous work also highlighted the possible contribution of arm elevation following an unexpected slip (Marigold and Patla 2002). Tang et al. (1998) also suggested that arms play a critical role in the recovery response, although they did not provide any detailed information. Arm movements can be used as a protective mechanism to avoid a potential injury from a fall or can be recruited as an active recovery strategy (Maki and McIlroy 1997; McIlroy and Maki 1995).

Therefore the primary purpose of this study was to investigate the roles of the unperturbed limb and the arms in the reactive recovery response to an unexpected slip induced by a set of steel rollers. Additionally, the adaptation to consecutive unexpected slips was investigated, as recent evidence suggests that muscle activity is attenuated following randomly experienced slips (Marigold and Patla 2002).
METHODS

Ten (6 female and 4 male) healthy, young adults from the University of Waterloo participated in this experiment. The mean (±SD) age, weight, and height of the participants were 21.2 ± 1.23 yr, 70.57 ± 13.6 kg, and 173.95 ± 12.12 cm, respectively. The University of Waterloo Ethics Committee reviewed and approved the study.

Slip apparatus and protocol

The slip was caused by a set of steel rollers that could be locked or unlocked. Foot contact (FC) with the rollers in the unlocked position caused them to rotate and thus provided a slip in the anterior–posterior (A–P) direction. A detailed description of the rollers can be found in a previous study (Marigold and Patla 2002). Briefly, the rollers (mass of 38.6 kg; static coefficient of friction = 0.04; dynamic coefficient of friction = 0.03) were mounted on a force plate, set flush in the middle of a 6.5-m-long, 3.8-cm-elevated wooden walkway with crash mats along the sides, and were visible at all times. The rollers were encased in a frame with a steel plate on the bottom that provided the contact with the force plate; thus forces were transmitted through the rollers’ frame to the force plate. During the experiment, participants wore a full-body harness with a rope attached. In the case of a fall, the experimenter would be able to catch the participant via the rope and a spotter trailing the participant could also assist. Prior to data collection, participants were allowed several practice trials to become acquainted with the walkway and to determine the starting position and walking velocity necessary to correctly step with their right foot (perturbed limb) on the rollers and their left foot (unperturbed limb) on the preceding force plate. During this time, 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. The participants wore running shoes for all trials and were told to look straight ahead while walking.

A total of 20 trials were collected for each participant. In all trials participants were not aware of the rollers’ condition (i.e., unlocked or locked). The first 10 trials were always locked and allowed the participants to become comfortable with the task and to provide a baseline for comparison with the later slip trials. In the subsequent 5 trials for each participant a randomly chosen trial provided the first slip. The first slip trial represented a “truly unexpected slip” in that no prior experience of a slip on this particular surface was available and no knowledge was provided as to the surface condition to the individual. Following this slip trial, 5 consecutive slip trials (i.e., rollers unlocked) were performed for each participant. At least 1 trial after these slip trials in which the rollers were locked without the participant’s knowledge and did not generate a slip was also included.

Electromyography (EMG) data collection and analysis

Ten pairs of bipolar surface EMG electrodes were used to record the activity of the unperturbed limb (i.e., the limb that did not make contact with the rollers) rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and the medial head of gastrocnemius (MG), bilateral gluteus medius (RGM and LGM), bilateral erector spinae (RES and LES), and bilateral deltoid (RD and LD). 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 single-pass, second-order Butterworth algorithm) with a custom-written program (Marigold and Patla 2002). Each muscle response profile for a slip trial was determined by subtracting the ensemble average profile of the control trials from the slip trial. Five control unperturbed trials prior to the first slip trial were used to generate the normal ensemble average profile. Subsequently, FC with the rollers, the onset, offset, and duration of each muscle burst for 2 s following FC with the rollers was calculated using a custom program (Marigold and Patla 2002). The presence of a recovery muscle response burst was defined as an increase in muscle activity that exceeded or fell below ±2 SD (depending on whether the burst was excitatory or inhibitory) for ≥30 ms. For each slip trial in all conditions, the muscle activity (i.e., area under the muscle response curve) was determined for the time interval of 120 to 200 ms after contact with the rollers to provide an indication of the recovery response adaptation observed. Activity from FC to 50 ms was also analyzed to determine whether any proactive activity was evident before making contact with the rollers.

Kinetic and kinematic 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 processed later 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. The zero transition from negative to positive values of the Fx (A–P force) for the force plate was used to distinguish between the braking (Fx/loading (Fy) and accelerating (Fx)/unloading (Fy) phase of the rollers. Four measures were determined from the force plate preceding the rollers, adjusted for body weight, and used for later analysis, including braking impulse, accelerating impulse, loading impulse, and unloading impulse. Two additional measures were also determined and adjusted for body weight, including the rate of loading (RoL) and the rate of unloading (RoUL). The braking impulse from the force plate with the rollers was also included since it has been shown to adapt to repeated unexpected slips (Marigold and Patla 2002). The braking impulse (Ns/kg) represented the area under the A–P force curve from FC on the force plate to the zero transition while the accelerating impulse (Ns/kg) represented the area under the A–P force curve from the zero transition to toe-off on the force plate (see Fig. 1). The loading impulse (Ns/kg) represented the area under the vertical force curve from FC on the force plate to the zero transition, while the unloading impulse (Ns/kg) represented the area under the vertical force curve from the zero transition to toe-off on the force plate (see Fig. 1). The RoL (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 (see Fig. 1).

Three OPTOTRAK 3D camera systems (Northern Digital) were used to collect the kinematic data. A total of 11 infrared emitting diodes (IREDs) were placed bilaterally and frontally at the level of the lateral malleolus, knee, greater trochanter, acromion, styloid process of the radius, and the xyphoid process of each participant. The
cameras’ sampled the IREDs at 60 Hz for 6 s with the kinetic and EMG data. These data were subsequently used to determine arm and unperturbed limb trajectories. The kinematic profiles of both the endpoints of the two arms (wrist markers) and the unperturbed limb (ankle markers) for the horizontal and vertical directions for the first slip were analyzed to describe the strategies used to recover balance after the perturbation. This included determining the onset of a change (>2 SD) from the control ensemble profiles and the direction of change in the displacement profiles. A videocamera (Panasonic) recorded the slip from the right side for qualitative observations.

Statistical analysis

A one-way (Muscle) repeated-measures ANOVA (RM ANOVA) on muscle onset latency was performed for the first slip trial. Post hoc analysis consisted of Tukey’s HSD Test. A paired t-test was performed comparing the two arms in terms of the onset of change of trajectory for the first slip trial. A one-way (Trial, n = 6) RM ANOVA using the first and subsequent five 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 variable. Furthermore, the muscle activity (i.e., the area under the response curve) for each muscle for the time interval of 120–200 ms following contact with the rollers was used for the analysis, considering each muscle separately. The time interval of 120–200 ms was used since the onset latency observed for the first slip occurred during this period.

A total of five trials (in which 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 data comparing the first slip with the true control trials to aid in explaining the recovery response. Two participants slid on the rollers with both feet for the first slip. For all impulse measurements these two participants were removed since this strategy would greatly affect the forces applied to the rollers. Statistical significance for all procedures was set at P < 0.05.

RESULTS

All individuals were successful in recovering balance following the slip during locomotion: no falls occurred. The first slip response was clearly different from the subsequent recovery responses to the unexpected slips. The differences were identifiable reactive recovery responses with no proactive changes in EMG patterns (Marigold and Patla 2002), a decrease in arm elevation after the first slip, absence of a toe-touch response from the unperturbed limb, and reduced magnitude of muscle responses. The first slip response and subsequent adaptation is described next.

First slip recovery response: muscle activation

To elucidate the first slip recovery response, muscle activity predominantly from the unperturbed limb as well as the upper body and arms were analyzed. Typical muscle activity profiles of RF, BF, TA, MG, LGM, RGM, LES, RES, RD, and LD for the ensemble average unperturbed trials and the unprocessed first slip trial (i.e., ensemble average not subtracted out from the slip trial) are shown in Fig. 2. The typical recovery response profiles (i.e., ensemble average subtracted out) exhibited by these muscles for the first slip are shown in Fig. 3. The figure illustrates the sequence of long-latency reflexes of these muscles in the recovery response. The 10 muscles showed a significant difference in onset latency (Fig. 4) in response to the first slip trial ($F(9,79) = 5.10$, $P < 0.001$). The MG (245.6 ± 45.7 ms) was significantly delayed in activating compared with every muscle except the RGM (236.6 ± 110.5 ms) and the LGM (188.2 ± 56.3 ms). Interestingly, the arm muscles, including RD (143.2 ± 22.1 ms) and LD (150.2 ± 34 ms), activated among the fastest even though the perturbation was experienced at the feet. There was no difference in onset between the arm muscles and those on the unperturbed limb that consisted of RF (161.6 ± 46.8 ms), BF (162.2 ± 22.4 ms), TA (153.1 ± 14.6 ms), and the upper body including LES (154.2 ± 24.4 ms) and RES (139.6 ± 45 ms). All muscles showed an excitatory burst response following the unexpected slip.

First slip recovery response: kinematics and kinetics of the unperturbed limb and arms

All but one participant demonstrated an arm elevation strategy as a recovery mechanism for the first slip trial. This consisted of a rapid increase in velocity to elevate both the arms up and forward simultaneously to maintain balance (see Fig. 5). The right arm horizontal trajectory showed no change from unperturbed trials; however, the right arm onset of a change in trajectory for the vertical direction was 281.5 ± 43.6 ms. The left arm onset of a change in trajectory was 252.8 ± 84.6 and 293.3 ± 58.4 ms for the horizontal and vertical directions, respectively. When the onset of change in trajectory in the vertical direction between the right and left arm was compared, no significant differences were found.

The unperturbed limb showed a decrease in velocity in all participants. Six of 10 participants rapidly lowered their unperturbed limb and 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 its normal trajectory). Two more participants managed to lower their unperturbed limb so that it slid on the rollers with the perturbed limb. Making contact with the ground, although only for a short time, provides a larger base of support, momentarily increases stability, and increases the likelihood of recovery. The onset latencies of a change in trajectory for the horizontal and vertical directions of the unperturbed limb were 316.7 ± 77.4 and 198.2 ± 39.5 ms, respectively. Figure 5 shows the ankle marker trajectory of the unperturbed limb of a representative participant and Fig. 6 illustrates the relationship between the ankle marker trajectories of the perturbed and unperturbed lower limbs.

To further characterize the first slip recovery response, impulses generated by stepping on the force plates (with and without rollers) were used to compare the first slip with normal, unperturbed, walking trials. The RoL was significantly reduced for the first slip (see Table 1), which may indicate a strategy whereby the body’s center of mass (CoM) has been positioned over the unperturbed (i.e., swing) limb for a longer period of time. The braking impulse from the force plate with rollers showed no significant difference (slip −0.353 ± 0.072 versus non-slip −0.329 ± 0.062 Ns/kg, $P > 0.05$). Impulses generated by the unperturbed limb off the force plate preceding the rollers also showed no significant differences between the first slip and control trials (see Table 1).

Recovery response to consecutive unexpected slips

There was a large recovery response seen for the first slip that gradually diminished with repeated unexpected slips. The adaptation varied depending on the measure. Six of 10 muscles dem-
onstrated a significant trial effect (see Fig. 7) for the magnitude of activity between 120 and 200 ms following FC on the rollers, including RF ($F(5,53) = 3.46, P = 0.009$), TA ($F(5,53) = 4.93, P = 0.001$), BF ($F(5,53) = 6.68, P < 0.001$), RES ($F(5,53) = 4.89, P = 0.001$), RD ($F(5,53) = 4.31, P = 0.003$), and LD ($F(5,53) = 3.27, P = 0.013$). This time interval is particularly important since the onset latencies for the first slip predominantly occurred within this range. The excitatory bursts seen in the first slip with RF and TA were attenuated after the fourth and third slips, respectively, and after the second slip for BF, RES, RD, and LD. With the exception of RF, all muscles showed only minor non-significant changes, if any, in response magnitude prior to

**FIG. 2.** Typical ensemble average profiles of muscle activity for the unperturbed walking trials and the first slip (prior to subtracting out ensemble average control trials) for participant 3 of the unperturbed limb (i.e., left) rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and medial head of gastrocnemius (MG). Muscles of the upper body and arms including bilateral gluteus medius (RGM and LGM), erector spinae (RES and LES), and deltoid (RD and LD) are also shown. FC, initial foot contact on the rollers.
120 ms following FC on the rollers. RF activity showed a significant trial effect during the 0- to 50-ms time interval: activity was significantly increased in slip 4, 5, and 6 compared with the first slip.

The unperturbed limb and arm trajectories returned to normal profiles for the majority of the participants within the first two slip trials as confirmed by visual inspection of the trajectory profiles. Figure 8 demonstrates the adaptation for the vertical trajectories of the unperturbed limb and arms. Only the vertical trajectories are shown since the strategies used are predominantly illustrated by...
The primary purpose of this study was to examine the role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip. There were no falls observed throughout the experiment. This was also found in our previous study (Marigold and Patla 2002). However, in studies on slipping that used some sort of contaminant (e.g., oil or soap), falls were reported (Cham and Redfern 2001). Contaminants may remain on the shoe surface even after the participants have slid past the area covered and impede full recovery resulting in a fall. Rollers do not leave any substance on the shoe and the brief exposure to the rollers may not be sufficient to produce a fall. Often, real-life situations with ice are similar to the latter method of inducing a slip in that no substance is left on the shoe; however, both methods are important to investigate further.

The results from the present study in conjunction with our recent findings highlight the importance of interlimb coordination in response to externally produced perturbations during gait. Furthermore, arm movements as a recovery response appear to be critical in recovering balance. The discussion to follow expands on these points and briefly examines the adaptation to consecutive unexpected slips.

**Unperturbed limb contribution to the reactive recovery response**

Muscles of the unperturbed limb were shown to rapidly activate following an unexpected slip during locomotion (140–246 ms). These muscle onset latencies were comparable to those found for the perturbed limb in Marigold and Patla (2002) and to both the perturbed and unperturbed limb in Tang et al. (1998) and are suggestive of polysynaptic long-loop reflexes.

The muscle activation pattern for the first slip in the unperturbed limb showed no clear distal-to-proximal or any other sequencing. The MG was significantly delayed while simultaneous activation of TA, RF, and BF was seen. Early TA activity leads to dorsiflexion at the ankle and is primarily responsible for preventing tripping (Winter 1991). RF activity causes knee extension, which is controlled through concurrent antagonistic control from BF (which is also involved in hip extension) (Winter 1991). The delayed MG prevents early tripping of the swing foot and allows knee extension early in the swing phase movement. Thus it appears as though individuals utilize an unperturbed limb extensor strategy whereby the knee and hip are extended and the limb is lowered to the ground as seen by the frequent use of a toe-touch response. Figure 5C shows the vertical trajectory of the unperturbed limb (inferred from a marker attached to the ankle) decreases (i.e., is lowered to the ground) through RF and BF muscle activation extending the knee and hip joint, respectively. This toe-touch response, albeit brief, provides added security to the individual by increasing the base of support and as a result increases stability. Marigold and Patla (2002) demonstrated the use of a toe-touch response in 67% of participants for the first unexpected slip. In the present study, 80% of the participants demonstrated this response. The rapid and beneficial nature of this response suggests that it is vital in maintaining dynamic stability in situations in which the CoM is displaced to the point of an impending fall. It can be speculated that falls in the elderly due to a slip may be a result of the inability to generate this rapid toe-touch response.

**Arm contribution to the reactive recovery response**

Following the first unexpected slip the arms are rapidly elevated forward and outward in an attempt to stabilize the backward displaced CoM. This arm elevation strategy has been demonstrated in older adults (Tang and Woollacott 1998) and young adults (Marigold and Patla 2002; You et al. 2001) following a slip during gait. The addition of arm EMG in the present study provides support for this strategy and illustrates the rapid nature of the arm movements. In fact, the right and left deltoid muscle onset latency was shown to be 143 and 150 ms, respectively, indicating a simultaneous activation with the lower limb musculature.

The arm elevation response was apparent even though no direct initial stretch of the arm muscles occurred from the roller-induced perturbation. By elevating the arms forward and outward, the CoM is shifted anteriorly after the slip causes it to be displaced backward (Marigold and Patla 2002). There were no differences in the onset of the arm muscles and the onset of a change in trajectory between arms. Even though the arms...
swing in opposite directions during locomotion, both were rapidly elevated. Arm muscle activity and subsequent movement has been demonstrated in response to externally applied perturbations during stance. The arm responses did not represent generic reactions but rather they were modulated depending on the magnitude of the perturbation (McIlroy and Maki 1995). In the present study, as participants adapted to the slip perturbations, the perturbations themselves became smaller (due to foot–surface interactions and loading changes) and the arm movements and muscle activity were concomitantly attenuated.

**Dynamic multilimb coordinated strategy**

The perturbed limb flexor strategy seen in Marigold and Patla (2002) in combination with the arm elevation and unperturbed limb extensor strategies in the present study point toward a “dynamic multilimb coordinated strategy” for dynamic stability. A functionally appropriate strategy has also been shown in the recovery response following a trip during locomotion (Eng et al. 1994). The CNS chooses to coordinate bilateral upper and lower limbs to stabilize the disturbed CoM and ensure safe forward progression off the slippery surface. Thus there appears to be a complex neural circuitry in which predominantly proprioceptive signals (i.e., muscle spindle input from ankle joint muscle stretch) trigger specific propriospinal pathways within the spinal cord that also receive cortical input to coordinate both the upper and lower limbs. These pathways can then be fine tuned over repeated perturbations as the CNS adapts. These propriospinal pathways appear to mediate interlimb reflexes coordinating fore- and hindlimbs in cats during locomotion by connecting the lumbar to the cervical enlargement within the spinal cord (Miller et al. 1975). A coordinated bilateral lower limb response in which the perturbed limb acts to reposition the displaced limb while the unperturbed limb provides compensation for the displaced body follows the findings of Berger et al. (1984). In this study, treadmill accelerations provided the perturbation during human gait (Berger et al. 1984). More recently, Dietz et al. (2001) demonstrated arm muscle activation following both mechanical perturbations induced by treadmill acceleration/deceleration impulses and electrical nerve stimulation of the distal tibial nerve. Furthermore, Dietz et al. (2001) have shown that there exists a task-dependent neuronal coupling between upper and lower limb muscles.

**FIG. 6.** Perturbed and unperturbed lower limb (i.e., ankle marker) trajectories for the first slip in the horizontal (direction of travel) and vertical directions. FC, foot contact by the perturbed limb on the rollers.

<table>
<thead>
<tr>
<th>Variable</th>
<th>n</th>
<th>Control</th>
<th>1st Slip</th>
</tr>
</thead>
<tbody>
<tr>
<td>RoL, N/kg/s</td>
<td>10</td>
<td>80.42 ± 14.04</td>
<td>63.38 ± 11.19*</td>
</tr>
<tr>
<td>RoUL, N/kg/s</td>
<td>10</td>
<td>–82.57 ± 7.83</td>
<td>–84.32 ± 9.29</td>
</tr>
<tr>
<td>Braking impulse, N/kg/s</td>
<td>10</td>
<td>–0.349 ± 0.047</td>
<td>–0.356 ± 0.071</td>
</tr>
<tr>
<td>Accelerating impulse,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N/kg/s</td>
<td>10</td>
<td>0.325 ± 0.047</td>
<td>0.332 ± 0.039</td>
</tr>
<tr>
<td>Loading impulse, N/kg/s</td>
<td>10</td>
<td>2.648 ± 0.236</td>
<td>2.654 ± 0.301</td>
</tr>
<tr>
<td>Unloading impulse, N/kg</td>
<td>10</td>
<td>2.177 ± 0.227</td>
<td>2.226 ± 0.180</td>
</tr>
</tbody>
</table>

Values are means ± SD. RoL, rate of loading; RoUL, rate of unloading. *Significantly different, $P < 0.05$. 

This table compares the first slip trial with normal, unperturbed walking.
FIG. 7. Adaptation of muscle magnitude to consecutive slips during the time interval of 120–200 ms following foot contact with the unlocked rollers. Muscles shown include the RD and LD, RES and LES, and the unperturbed limb BF, RF, and TA.
Adaptation to consecutive unexpected slips

As a follow-up to the initial study, the adaptation for the arms and unperturbed limb as well as the force plate measures was established to determine whether consecutive slips had an effect and to determine whether the unperturbed limb muscle adaptation differed from the perturbed limb. Following the first slip, participants demonstrated the use of a surging strategy as described in Marigold and Patla (2002). This strategy consisted of holding the arms forward and outward slightly while the unperturbed limb delayed landing and the perturbed limb slid on the rollers rather than stepping off quickly. A similar strategy has been shown by other researchers in response to perturbations (Buchanan and Horak 1999 2001; Corna et al. 1999).

The time for the unperturbed limb musculature to adapt (i.e., muscle magnitude) differed depending on the muscle in question. The time for adaptation ranged from after the second slip to after the fourth consecutive slip. The delayed adaptation for RF and TA may be a result of the importance of these two muscles in the recovery response to an unexpected slip. Maintaining a strong TA activation leads to ankle dorsiflexion and prevents tripping of the swing foot, while maintaining a strong activation in RF causes knee extension and makes it easier to elicit a toe-touch response if necessary. Thus continued recruitment of these two muscles ensures safe travel across the slippery surface.

The braking impulse showed that individuals adapted to the slip in terms of this measure within two slip trials. A previous study with randomly induced rather than consecutive slips showed adaptation for the braking impulse to occur within one slip trial (Marigold and Patla 2002). Nashner (1976) showed that the initial response to a sudden change in the type of perturbation 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). Although the initial response here was not necessarily inappropriate, the delayed adaptation was similar to that observed by Nashner (1976). At least two possible reasons exist for explaining the delayed adaptation in the braking impulse as well as the upper and lower limb musculature. Since participants experienced several trials in which the rollers were locked and did not generate a slip and then suddenly a slip was induced during one trial, they figured two consecutive slips were unlikely and did not adjust accordingly. Another reason may be that the excitability of the motoneuron pool controlling the limbs requires more than one stimulus to modify its response.

Nonetheless, adaptation to repeated unexpected slips depends on whether they are presented randomly or consecutively and future investigations into slipping responses should take this into consideration for analysis and experimental design purposes.

CONCLUSION

It is becoming increasingly apparent that coordination between the two lower limbs is vital in maintaining dynamic stability following a perturbation during gait. The previously observed perturbed limb flexor strategy in combination with the arm elevation and unperturbed limb extensor strategies in the present one point toward a bilateral upper and lower limb coordination that can be considered a dynamic multilimb coordinated strategy for dynamic stability. The roles of the arms and unperturbed limb are fundamental in the reactive recovery response to an unexpected slip. The arms assist in shifting the CoM anteriorly after it is displaced posteriorly by the induced slip while the unperturbed limb lowers and briefly touches the ground (i.e., toe-touch response) to widen the base of support and increase stability. Future studies on perturbations during locomotion should focus not only on lower limb parameters but also on upper limb dynamics in the recovery response, as a complete picture is critical in understanding the nature of the recovery response.

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