Control of Dynamic Stability During Gait Termination on a Slippery Surface

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Oates, A. R., A. E. Patla, J. S. Frank, and M. A. Greig. Control of dynamic stability during gait termination on a slippery surface. J Neurophysiol 93: 64–70, 2005. First published August 4, 2004; doi:10.1152/jn.00423.2004. There are three common ways by which to successfully terminate gait: decreased acceleration of whole-body center of mass (COM) through a flexor synergy in the hind leg, increased deceleration of whole-body COM through an extensor synergy in the front limb, and an energy/momentum transfer to dissipate any remaining momentum if the first two strategies are unsuccessful. Healthy individuals were asked to stop on a slippery surface while we examined their unexpected response to the slippery surface. Kinetic data from the forceplates revealed lower braking forces in the slip trials compared with normal gait-termination trials. Subjects were unable to control their center of pressure (COP) to manipulate the COM as revealed by increased deviations and maximum absolute ranges of COP movement. Subject COP deviated farther in both horizontal planes and lowered further during the slip compared with normal gait-termination trials. Arm movements were effective in dissipating forward COP movement. In addition, there likely was a transfer of forward to lateral momentum to stop forward progression. All recorded muscle activity in the lower limbs and back increased during the slip to provide support to the lower limbs and correct upright balance. The trailing limb shortened its final step to provide support to the lowering COM. The balance-correction response seen here resembles previous reactions to perturbations during locomotion suggesting there is a generalized strategy employed by the nervous system to correct for disturbances and maintain balance.

INTRODUCTION

Gait termination (GT) is defined as the transient period from repetitive gait to a full stop (Jian et al. 1993). Stopping is a great challenge to the body as the nervous system must effectively change the body from a dynamic to a static state. Three common ways by which to successfully terminate gait include: decreased acceleration of whole-body center of mass (COM) through a flexor synergy in the hind leg (Hase and Stein 1998; Jaeger and Vanitchatchavan 1992), increased deceleration of whole-body COM through an extensor synergy in the front limb (Hase and Stein 1998; Jaeger and Vanitchatchavan 1992), and an energy/momentum transfer through a toe rise (Hase and Stein 1998) or a momentum transfer to another plane of movement (O’Kane et al. 2003).

Muscle synergies employed by the CNS manipulate limb movement to alter the center of pressure (COP) beneath the feet. The COP controls the COM during gait termination (Jian et al. 1993) and can influence COM position in three ways (B. McGowan, unpublished observations): first, a change in foot placement, such as an increase in step length, will move the COP ahead of the COM and increase the ability to provide a braking force. Second, limb loading/unloading strategies can also be used to control the COP/COM. A flexor synergy in the hind leg taking the final step before termination unloads that limb thereby decreasing the acceleration and lowering the COM. Loading the limbs in the final stance phase, an extensor synergy, increases the braking force and decelerates the COM (Hase and Stein 1998). Limb loading/unextension can also raise or shift the COM, thereby converting some kinetic energy to potential energy or transferring momentum to another plane to dissipate forward momentum (O’Kane et al. 2003). Finally, the excursions of the COP within the base of support (BOS) can influence the COM position and assist gait termination.

A slippery surface removes the ability to effectively manipulate the COP and eliminates a large part of COM-control during movement. Previous studies investigating slip responses during gait report a rapid onset of a flexor synergy to lower the COM and improve stability as well as arm elevation to stabilize the unexpected COM displacement (Cham and Redfern 2001, 2002; Marigold and Patla 2002; Marigold et al. 2003). The purpose of the present study was to examine the response to an unexpected slip during gait termination. Slip responses during gait termination are expected to parallel those measured in steady-state gait but increase in magnitude as the loss of COP control during gait termination is hypothesized to be more detrimental than during steady-state gait.

METHODS

Gait termination (GT), on a normal and a slippery surface, was investigated in eight healthy, young adults [4 males and 4 females, age = 24 ± 3 (SD) yr]. Experimental setup included a 4-inch-high wooden walkway with aluminum rollers covering one forceplate (see Marigold and Patla 2002 for detailed description of the roller apparatus). A set of 10 walk-through (WT) trials were performed along the walkway to collect baseline gait data. The subject then performed a series of 21 trials, of which a random 5 of the first 20 trials required termination on a set of locked rollers [non-slippery stop (NS) trials]. As the subject stepped with the left foot on the first forceplate (covered by wood), a monitor at the end of the walkway signaled for the subject to stop with both feet on the second forceplate (covered by the rollers) (Fig. 1). The 21st trial always signaled the subject to stop. For the 21st trial, however, the rollers were unlocked without the subject’s knowledge to create a slippery surface [slippery stop (SS) trials] and therefore a purely unexpected slip trial. The rollers were aligned so the slip was only in the direction of progression (along the x axis). The protocol was approved by the University of Waterloo Ethics committee and safety measures were taken to ensure subjects did not fall during SS trials.

Two AMTI forceplates were used to collect ground reaction forces sampled at 2,400 Hz. Previous testing (A. Oates, unpublished obser-

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vations) of the forceplates with the wooden platform and roller coverings demonstrated accurate (within 2%) data recording with the exception of the natural frequency and the sensitivity of the system. These system differences were deemed acceptable for this experiment. Forceplate data were low-pass filtered at 60 Hz and analyzed using a custom program.

Ground reaction forces represent the algebraic sum of the mass-acceleration products of all segments in the body and therefore provide a representation of COM control. Braking impulse was calculated as the integration of the horizontal ground reaction force in the direction of progression over a set time period. The integration period was determined by the length of foot contact on the rollers during the SS trials. This integration period was constant for a subject but varied between subjects according to the length of foot contact by each subject on the slippery surface (range = 0.12–0.35 s). The braking impulse and the peak braking force were compared between NS and SS conditions. The average range of COP movement [calculated as the root-mean-square (RMS) of all deviations in the x and z axis] as well as the maximum range of COP was compared between all conditions.

Three Optotrak (Northern Digital) cameras recorded kinematic data from 21 infra-red emitting diodes (IREDS) at 60 Hz to create a 12-segment model for COM calculation. IREDS were placed at: xyphoid process and bilaterally at fifth metatarsal, heel, lateral malleolus, lateral femoral condyle, greater trochanter, ASIS, acromion process, olecranon, radial styloid, medial clavicle. Raw data were processed using Optofix and CoFm software (MLihac Kinetics) and low-pass filtered at 6 Hz. Step length and width values were measured from the heel markers at the point of heel contact on the forceplates. To calculate the contribution of the arm segments to the slip-recovery response, the arms were removed from the COM model to create a 10-segment COM model. The resulting arm-less COM peak displacements and peak momentum profiles were compared to those with arms. (Note: arm marker data were missing for 2 subjects. These 2 subjects therefore were not included in the comparison between the full COM model and the arm-less COM model). Final COM position in the x axis, the peak displacements of the COM in the vertical (y axis) and horizontal (z axis) were calculated both with and without arm segments for the gait termination trials. COM momentum profiles were compared between NS and SS trials to identify any momentum transfers during GT. Instantaneous COM momentum values were compared at peak values of the NS trials after heel contact on the rollers.

Muscle activity was recorded from 10 pairs of bipolar Kendall Meditrace surface electrodes: tibialis anterior (TA), soleus (SOL), rectus femoris (RF), biceps femoris (BF), and lower erector spinae (LES), bilaterally sampled at 2,400 Hz (0.5–1 K gain with a Bortec AMT-8 amplifier). Electromyographic (EMG) data were analyzed using a custom-designed Matlab program (Mathworks, Natick, MA) which full-wave rectified, filtered (2nd-order Butterworth with a low-pass frequency cut-off of 10 Hz) and aligned the data with heel contact on the forceplates. For comparison purposes, WT trials and NS trials were compared by aligning the data to heel contact on the rollers. These alignment points were chosen to illustrate any differences in behavior that accompanied the differences due to surface conditions.

Significant muscle-activity changes (defined as a change beyond 2 SD of the average muscle activity in the 1 s before heel contact with a minimum duration of 50 ms) were determined and difference latencies (average WT trials subtracted from average NS trials and average NS trials subtracted from SS trials) were calculated (Marigold and Patla 2002). The differences between WT and NS trials will be referred to as latencies, whereas the differences between NS and SS trials will be referred to as difference latencies. When comparing the WT and NS trials, a significant change in activity is reported only when that muscle showed significantly different activity in 60% of the NS trials. Preplanned comparisons, using paired t-tests, were conducted for WT versus NS (α = 0.05). Nonparametric Wilcoxon tests were conducted for the NS versus SS trials because of the differences in sample size (n = 35 vs. n = 8, α = 0.05).

RESULTS

Subjects were able to stop successfully on the rollers in 35/40 NS trials. In two unsuccessful NS trials (1 trial each for 2 subjects), the subject reported that he/she was not paying attention to the monitor at the end of the walkway. For the remaining three unsuccessful trials (all within the same subject), the subject seemed to be walking too fast to stop with both feet on the rollers. These five unsuccessful NS trials were not included in the analysis. All subjects were able to regain balance and eventually stop safely (i.e., without falling or requiring assistance to maintain balance) during the SS trials.

Braking impulse and force

Braking force illustrates the amount of force generated to stop forward movement. Subjects exerted a significantly lower braking impulse during SS trials compared with NS trials (P = 0.0120; Fig. 2, A and B). The peak braking force, however, did not differ significantly between gait termination conditions (Fig. 2B). The slippery surface prevented the subjects from developing a sufficient braking impulse to stop forward progression.
trials (\(P\) significantly larger in the WT trials compared with the NS trials). In the direction of progression (COPX), the RMS was maximum range of COP (with SE). A and B: \(^*\), significant difference between conditions (\(\alpha <0.05; n = 8\) subjects).

**Center of pressure**

The RMS of the COP in all directions differed significantly between both WT and NS and NS and SS conditions (Figs. 3A). In the direction of progression (COPX), the RMS was significantly larger in the WT trials compared with the NS trials (\(P = 0.0227\)), but there was no difference in the maximum range of COPX values between the WT and NS conditions (\(P = 0.9009; \text{Fig. 3B}\)). The increased deviation is expected as the COP travels under the entire length of the foot as the subjects continue walking past the forceplate. Subjects likely used their entire plantar surface to move the COP during both static foot placements of WT and NS trials, a likely explanation for the lack of difference between the maximum range of COPX movement between the WT and NS trials. In the mediolateral plane (COPZ), both the RMS (Fig. 3A) and maximum range (Fig. 3A) values were significantly greater in the NS trials than the WT trials (\(P = 0.0002\) for RMS and \(P = 0.0011\)). As both feet are placed on the forceplate during gait termination, the COP has a greater area within to move and therefore the increased deviations and ranges of COP values are expected when comparing NS to WT trials.

A comparison between the NS and SS trials reveals an increase in all four variables during the slip (Fig. 3, A and B): RMS, \(P = 0.0120\) for COPX and \(P = 0.0120\) for COPZ; maximum range, \(P = 0.0170\) for COPX and \(P = 0.0120\) for COPZ. The increased deviations and ranges indicate the foot was not able to remain static on the slippery surface as the foot slid forward. Subjects were therefore not able to stop successfully with the same COP pattern.

**Step parameters—length and width**

Average step length was \(80.8 \pm 5.3\) (SD) cm for WT trials, \(80.3 \pm 3.4\) cm for NS trials, and \(82.2 \pm 3.6\) cm for SS trials. Average step width was \(26.6 \pm 2.8\) cm for WT trials, \(28.1 \pm 3.7\) cm for NS trials, and \(28.3 \pm 2.9\) cm for SS trials. Unlike previous investigations (B. McGowan, unpublished observations), there was no significant difference between WT and NS trials in either step length or width. The lack of difference between the WT and NS conditions suggests that subjects did not attempt to use changes in step parameters to terminate locomotion. There were also no differences in step parameters between the NS and SS trials which confirms that subjects were unable to anticipate the slippery surface.

**Center of mass**

The COM moved significantly more in all three planes during the SS compared with the NS trials both with and without arms (Fig. 4, A and B). In the direction of progression, the COM moved on average \(51.6 \pm 7.7\) cm with arms in the NS trials, \(51.4 \pm 6.8\) cm without arms in the NS trials, \(70.8 \pm 11.7\) cm with arms in the SS trials, and \(76.3 \pm 14.5\) cm without arms in the SS trials. In the mediolateral plane, the COM moved on average to the right \(2.38 \pm 1.6\) cm with arms in the NS trials, \(2.56 \pm 1.6\) cm without arms in the NS trials, \(5.55 \pm 2.1\) cm with arms in the SS trials, and \(6.26 \pm 3.3\) cm without arms in the SS trials. Vertically, the COM lowered on average \(0.60 \pm 0.34\) cm with arms in the NS trials, \(0.68 \pm 0.35\) cm without arms in the NS trials, \(3.17 \pm 1.9\) cm with arms in the SS trials, and \(5.61 \pm 4.2\) cm without arms in the SS trials. An increased travel distance demonstrates that the subjects were unable to stop forward progression on the slippery surface as effectively as stopping on the normal surface, a result supporting the increased deviation of the COPX. The large mediolateral movement parallels the COP data that also showed greater mediolateral movements during SS trials compared with the NS trials. Subjects significantly lowered their COM during the SS trials in an attempt to regain stability on the slippery surface.

COM momentum (Fig. 5A) was significantly different during the SS trials when compared with peak vertical NS trial values (Fig. 5B). Both horizontal velocities were significantly greater in the SS trials than the NS trials; subjects were sliding forward and their COM was traveling to the right faster than during NS trials when slipping on the rollers. The vertical COM momentum was increasing in the NS trials and decreasing in the SS trials. The lowering of the COM is likely a response to the slip to stabilize the body and maintain balance. The increase in the COMZ momentum could be the result of a
momentum transfer from A-P to M-L to dissipate forward momentum. Arm movement did not have a significant effect on COM displacement. Arm movement did, however, have a significant effect on COM momentum. When peak COM momentum values were compared between SS trials using a full or arm-less COM model, there was significantly higher forward momentum without the arms in the model (Fig. 6). The increased forward momentum suggests that the arms were effectively used to arrest forward momentum during the slip, and, as the arms were neither fully flexed nor abducted, the arms could have possibly assisted with a transfer of momentum from forward to lateral.

Muscle activity

NON-SLIPPERY STOPS VERSUS WALK-THROUGH. On average, all muscles, except for the right TA and right RF, showed significantly different activity during the NS compared with the WT trials (Fig. 7 for the right limb and Fig. 8 for the left limb). Average latencies between WT and NS trials ranged from 57 ms (right LES) to 332 ms (right BF; Table 1). Inhibition was

FIG. 5. A: average COM momentum profiles. Vertical line indicates heel contact on the rollers. Solid lines represent SS trials, dashed lines represent NS trials. (n = 6 subjects). B: comparison at peak vertical COM momentum during NS trials (with SE). *Significant difference between conditions (α < 0.05); n = 6 subjects.

FIG. 6. Average peak COM momentum values compared between a full and an arm-less COM model (with SE). COMX and COMZ values were compared at maximum values, COMY values were compared at the minimum value. *, significant difference between conditions (α <0.05; n = 6 subjects).

FIG. 7. Representative right limb EMG from 1 subject. Vertical line represents heel contact on the rollers. Horizontal axis is time (s). Signal to stop at 0 s. Vertical axis is arbitrary units. (n = 1 subject).

FIG. 8. Representative left limb EMG from 1 subject. Vertical line represents heel contact on the rollers. Horizontal axis is time (s). Signal to stop at 0 s. Vertical axis is arbitrary units. (n = 1 subject).
In this study, we show that subjects unload their left limb to decrease acceleration, load their right limb to increase braking force, and manipulate the COP movement underneath the feet to stop successfully. When attempting to stop on a slippery surface, each subject displayed a slightly different reaction yet a generalized response to the slippery surface emerged which included an arm raise, a shortened final step, and increased lower limb muscle activity to support the lowering COM; all strategies were employed to regain stability and prevent a fall. The reaction to the slippery surface in the present study is similar to previously reported perturbation reactions during locomotion (e.g., Marigold and Patla 2002; Misiaszek 2003), suggesting a generalized recovery strategy to perturbations during walking that attempts to maintain balance and the specific locomotor task.

**DISCUSSION**

In this study, we show that subjects unload their left limb to decrease acceleration, load their right limb to increase braking force, and manipulate the COP movement underneath the feet to stop successfully. When attempting to stop on a slippery surface, each subject displayed a slightly different reaction yet a generalized response to the slippery surface emerged which included an arm raise, a shortened final step, and increased lower limb muscle activity to support the lowering COM; all strategies were employed to regain stability and prevent a fall. The reaction to the slippery surface in the present study is similar to previously reported perturbation reactions during locomotion (e.g., Marigold and Patla 2002; Misiaszek 2003), suggesting a generalized recovery strategy to perturbations during walking that attempts to maintain balance and the specific locomotor task.

**Walk-throughs versus gait termination**

GT differed from normal WT trials primarily by decreased forward propulsion and increased deceleration of the body after the stop signal. There was no push-off phase after the right foot was placed on the locked rollers through the ground reaction forces. Co-contraction at the hip and knee slowed the left leg during the final swing phase, whereas inhibition of the left SOL decreased the push-off forces. The right limb increased its braking force through an extensor synergy (increased RF and SOL activity) while the remaining muscles in the right limb (TA and BF) provided support through an increase in stiffness and, therefore stability. Trunk movement was controlled through bilateral LES activation. Although muscle activity from large groups such as the gluteals and vasti group were not recorded, their activity likely coincided with the BF and RF muscles respectively to assist with the extensor synergy and decelerate forward movement.

Compared to previously reported results (Crenna et al. 2001) the onset of muscle activity signaling the initiation of gait termination were much quicker for the right limb [average latency ~180 ms for the right limb compared with ~330 ms for the swing limb in Crenna et al. (2001)], whereas the left/stance limb latencies match very closely [150 ms for the left limb and ~150 ms for the stance limb (Crenna et al. 2001)]. There was no clear recruitment order evident in our study, whereas Crenna et al. (2001) found a distinct distal-to-proximal activation in the stance limb (our left limb) and a proximal-to-distal activation in the swing limb (our right limb). These differences in recruitment order may be related to the experimental protocol. The present study used a 25% chance of gait termination, whereas the comparable study (Crenna et al. 2001) employed a 50% occurrence of gait termination. Higher probability of GT in the study by Crenna et al. (2001) would reduce the variability of the program for GT. Perhaps the fewer termination trials in the current study allowed for larger variance thereby making it difficult to discern any clear ordering of muscle activation patterns. Another source of variance between the two studies could be the selection of trials for analysis: the present study included all successful NS trials (i.e., the subject stopped with both feet on the rollers), whereas it is unclear if all of the stop trials were included for analysis in Crenna et al. (2001).

Flexor and extensor synergies (Hase and Stein 1998) were used to load and unload the limbs for effective gait termination as shown in the kinetic data from the forceplates. That is, the flexor muscle activity increase in the left limb decreased the push-off force under the left limb. The braking forces under the right limb increased as a result of increased extensor activity. Through the flexor/extensor synergies, subjects used the ground reaction forces to manipulate the COP and decelerate the COM to a stable, stationary position.

The muscle activation patterns in the present study are comparable to those of Hase and Stein (1998), who reported an inhibition in the left limb (comparatively) SOL and a similar latency of left TA activity [150–200 ms reported in Hase and Stein (1998), ~140 ms in present study]. Differences exist.
when comparing the latencies of the left and right LES muscles; the present study found latencies around 115 and 57 ms, respectively, where Hase and Stein (1998) reported a bilateral activation of the LES muscles ~200 ms. In general, the present study found latencies from ~15 to 150 ms shorter than those reported in Hase and Stein (1998). The differences may be due to the stimulus provided to initiate gait termination. Hase and Stein (1998) used electrical stimulation of the superficial peroneal (SP) nerve, whereas the present study used a visual cue. Electrical stimulation of the SP nerve may have slightly prolonged activation based on the amount of neural processing involved to perceive the signal and initiate GT and also the experience interpreting the cue. A visual cue requires perception at the cortical level followed by appropriate cortical-spinal commands to stop walking. Stimulating the SP nerve requires perception of the cue, interpretation of the cue as a signal to stop walking, and then initiation of a GT program: A route that involves a signal traveling up the spinal cord to the cortex, cortical processing and subsequent cortical-spinal commands to stop walking. The sight of a stop sign is a regular occurrence in everyday life and is easily interpreted as a cue to stop. SP nerve stimulation, however, is not regularly used as a cue to stop movement and may have required more processing to understand the significance of the cue.

Gait termination on a normal surface versus a slippery surface

GT on the SS of the unlocked rollers proved to be a balance-challenging task. Normal stopping strategies were insufficient to maintain COM trajectories while slipping. Subjects were unable to generate enough braking force to stop the forward progression of the COM within the same limits as normal gait termination. In all SS trials, subjects shortened their last step with their left leg (i.e., the step that would place the left foot beside the right foot on the rollers). This small step enabled the subjects to increase their base of support during the SS trials; this would allow the ground reaction forces (i.e., the COP) under the left foot to corrall the COM and help prevent a fall. Subjects also raised their arms and lowered their COM to stabilize their body and stop walking.

Every muscle recorded increased its activity to support the body, stop forward movement and restore stability. All of the lower-limb muscle activity increased to support the legs and the whole-body COM and, most likely, to stiffen the lower limb joints throughout balance recovery. The difference latencies between the NS and SS trials suggest that the nervous system is able to detect the slip and elicit a behavioral response in as little as 60 ms; these latencies suggest long-latency reflexes (57 ms) as well as voluntary reactions (178 ms) to the slippery surface (Pearson and Gordon 2000). The large left TA activity may have created a toe lift to prepare for the shortened step. The shortened step and increased TA activity resembles the startle response observed by Nieuwenhuijzen et al. (2000). The startle response is an adaptive response in that the nervous system attempts to adopt the most stable posture in an unstable situation. The arm raise and increased TA activity helped to stabilize the falling COM during the slip. While all subjects were surprised by the slippery surface, it is likely that any apparent startle response was initiated as part of a balance-recovery program to reestablish stability but was not the primary method by which subjects successfully terminated gait.

Medial-lateral plane movement was increased during SS trials as evidenced in the larger COP and COM deviations while slipping. This increase in movement cannot be attributed to the rollers because they permit slipping only in the direction of progression. A counter-clockwise twist of the body, caused by the right foot sliding forward while the left foot was behind the rollers, may have initiated the medial-lateral movement by turning the body axis from its original alignment. A twist may also have been a reaction to and not a consequence of the right foot sliding forward. If the basic GT strategy (involving loading and unloading the limbs and COP manipulation) is not effective, the CNS may have attempted to transfer part of forward momentum to lateral momentum; a transfer that would involve some rotation about the vertical axis.

To stop successfully on the rollers, subjects may have attempted to transfer forward to lateral momentum as seen in previous research on patients with balance deficits (O’Kane et al. 2003). Previous GT investigations in both healthy (Hase and Stein 1998) and neurologically impaired individuals (O’Kane et al. 2003) observed energy/momentum transfers during GT. Hase and Stein (1998) suggested that subjects used a toe-raise to dissipate forward momentum if they were unable to either effectively dissipate push-off force or generate sufficient braking force. By transferring momentum between axes, subjects in the present study may have utilized a lateral limb load/unload strategy instead of an anterior-posterior load/unload strategy found in normal stopping (Hase and Stein 1998; B McGowan unpublished observations). O’Kane et al. (2003), reported that both cerebellar and vestibular patients used a forward to lateral energy transfer to assist GT. The cerebellar patients were unable to control the eccentric muscle activity required to absorb the forward momentum, whereas the vestibular patients were not able to detect the amount of acceleration of the body until the last step when the visual and proprioceptive systems provided information about the velocity of movement. The awareness of a lack of deceleration in the vestibular patients during this last step would eliminate the usefulness of a reduced push-off power (i.e., it would be too late at that point in GT) and therefore require a large braking force and a momentum transfer to effectively dissipate forward momentum. These findings applied to the current study suggest that, when traditional stopping strategies such as decreased push-off and increased braking forces fail to stop forward progression, subjects attempt to transfer forward momentum to lateral momentum to effect safe, stable GT.

Lowering the COM increases stability (Cham and Redfern 2001; Marigold and Patla 2002; Tucker et al. 1998) and was a strategy used by all subjects during SS trials. The lowering of the COM was likely the result of the flexor synergy often seen in slips (Brady et al. 2000; Cham and Redfern 2001, 2002; Marigold and Patla 2002), evidenced by the increased muscle activity in the hip, knee, and ankle flexors of both limbs. The slip of the right foot on the rollers may have passively contributed to the lowering of the COM. Because in some subjects, the COM began moving upwards before the foot had stopped sliding forward, the observed COM lowering cannot be considered a passive consequence of the foot sliding on the rollers. This suggests that lowering of the body COM is most probably an active control strategy.
Arm movement was ineffective on average in altering the COM displacement during SS trials. The arms did, however, make a significant difference in the peak forward momentum values suggesting the arms helped dissipate forward momentum. The arm strategy, therefore, is used to control movement velocity instead of displacement. This protective arm elevation strategy is often seen in slips and is coordinated with the lower limb slip response (Haridas and Zehr 2003; Marigold and Patla 2002; Marigold et al. 2003; Misiaszek 2003). The interlimb coordination serves to diminish the whole-body COM momentum during the slip, minimize the perturbation, and assist in balance recovery.

**Neural mechanisms**

Normal GT was successfully performed in the majority of trials. The instructions given to the subject about the requirement to stop when the visual cue was given allowed subjects to plan a GT strategy. The timing of the cue required the subject to stop within one step. During this final step, the subject would have had to process the visual cue as a stop signal and initiate a GT program involving an extensor/flexor or load/unload synergy in the limbs. The number of catch (WT) trials and the timing restraint on the response removes the chance for any anticipatory actions. The change in motor activity from a locomotor to a GT program was initiated as early as 57 ms and took as long as 332 ms on average. The GT program was likely initiated by the visual cue and monitored by the visual, proprioceptive, and vestibular sensory systems.

The nervous system initiated slip responses in some muscles in as little as 36 ms. These initial reactions are suggestive of stretch reflex or short-latency reactions (Pearson and Gordon 2000). On average, most motor activity recorded was between 50 and 200 ms, suggestive of polysynaptic or long-latency reflexes (Pearson and Gordon 2000) and simple reaction times (Hase and Stein 1998). It is possible that the vestibular system detected the slip through head acceleration (Horak et al. 1994) and initiated extensor activity to support the body during the perturbation. Cutaneous receptors on the plantar surface of the foot (Perry et al. 2000) and load-sensitive afferents in the ankle extensors (Misiaszek et al. 2000) likely detected the slip and, through their afferent feedback, helped initiate a polysynaptic response. It is unlikely that the visual system was able to detect the slip and, in sufficient time, elicit a visually based balance-correcting response due to the relative slowness of normal visual reaction time (~100-ms delay compared with proprioceptive-based balance-correcting responses (Pearson and Gordon 2000)). Comparison of the slip reaction during GT seen here to previous studies involving perturbations to either the support surface (e.g., Cham and Redfern 2001, 2002; Marigold and Patla 2002; Marigold and Patla 2003) or the loading of the lower limbs during steady state gait (Misiaszek et al. 2003; Misiaszek et al. 2000) suggests that the CNS generates a common balance-recovery strategy when equilibrium is disturbed during locomotor activities. The reaction latencies could be interpreted as responses from spinal and supraspinal structures (such as the lateral vestibular nucleus, reticular formation, and motor cortex) charged with monitoring locomotor activity and maintaining dynamic balance throughout.

In conclusion, muscle responses to slipping are comparable to responses found in previous experiments (Cham and Redfern 2001, 2002; Marigold and Patla 2001; Marigold et al. 2003) as are the arm responses (Marigold et al. 2003) and shortened step (Cham and Redfern 2002; Marigold et al. 2003), suggesting a general balance recovery strategy when a slippery surface is encountered during GT. This recovery strategy includes an overall increase in muscle activity to increase lower extremity joint stiffness, lowering of the COM, a shortened step, and arm elevation; all designed to increase stability and maintain balance during the slip. GT on a slippery surface employs the same recovery strategy but includes an arm raise to stop forward progression and transfer forward to lateral momentum to stop safely and prevent a fall.

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