Earth-Referenced Handrail Contact Facilitates Interlimb Cutaneous Reflexes During Locomotion

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Lamont EV, Zehr EP. Earth-referenced handrail contact facilitates interlimb cutaneous reflexes during locomotion. J Neurophysiol 98: 433–442, 2007. First published May 23, 2007; doi:10.1152/jn.00002.2007. The purpose of this study was to investigate whether the gating of interlimb cutaneous reflexes is altered by holding an earth-referenced handrail during locomotion. In the first experiment, subjects performed locomotor tasks of varying difficulty (level walking, incline walking, and stair climbing) while lightly holding an earth-referenced rail. In the second experiment, the extent of rail contact and nature of the rail stability (e.g., fixed vs. mobile rail) were varied while subjects performed incline walking. Cutaneous reflexes were evoked by delivering trains of electrical stimulation to the sural nerve at the ankle. EMG data were collected continuously from muscles in the upper and lower limbs and trunk. Results showed that modulation of reflexes across the body changed when the rail was held. Most interestingly, a facilitatory reflex in the shoulder extensor posterior deltoid emerged during swing phase only when subjects held a rail. This facilitatory reflex was largest during the more challenging tasks of incline walking and stair climbing. A similar reflex facilitation was observed in the elbow extensor triceps brachii. The observed facilitation of reflexes in triceps brachii and posterior deltoid was specifically expressed only when subjects held an earth-referenced rail. This suggests that interlimb reflexes in arm extensors may be enhanced to make use of a supportive handrail for stability during gait. Therefore, holding a rail may cause global changes in reflex thresholds across the body that may have widespread functional relevance for assisting in the maintenance of postural stability during locomotion.

INTRODUCTION

Cutaneous reflexes evoked in leg muscles by stimulation of nerves innervating the foot (i.e., segmental cutaneous reflexes) are precisely gated and have a functional role in maintaining and restoring stability during standing (Aniss et al. 1988, 1990, 1992; Burke et al. 1991) and walking (reviewed in Zehr and Stein 1999; also see Haridas et al. 2005). For example, stimulation of the sural nerve (innervates the lateral foot margin) evokes facilitatory reflexes in tibialis anterior (TA) during the early swing phase of walking, thereby assisting the ankle to dorsiflex and step over an obstacle rather than tripping on it. The same stimulation evokes suppressive reflexes in TA at the end of swing, allowing the foot to make stabilizing ground contact as rapidly as possible (Duyssens et al. 1990; Van Wezel et al. 1997; Yang and Stein 1990; Zehr et al. 1998). Therefore, segmental cutaneous reflexes in leg muscles are exquisitely sensitive to the locomotor state of the lower limbs and allow for specific and appropriate responses to maintain stability and forward progression.

It is less clear whether cutaneous reflexes evoked in arm muscles by stimulation of nerves innervating the foot (i.e., interlimb reflexes) have a functional role in maintaining stability during locomotion. Behaviorally, the arms can be observed to play a role in common stabilizing reactions including raising the arms or grasping handrails (Marigold et al. 2003; McIlroy and Maki 1995). The extent to which reflex pathways are involved in recruiting the arms to aid in stability is unknown. Interlimb reflexes can be evoked in arm muscles after electrically or mechanically perturbing the foot (Dietz et al. 2001; Haridas and Zehr 2003), suggesting that these reflexes are involved in assisting the coordination of the arms and legs during locomotion. However, these reflexes could not be specifically linked to a role in stumble correction. Misiaszek (2003) reported rapid responses in the arms after a backward pull of the trunk during locomotion; however, responses varied greatly between subjects, likely as a result of the large number of degrees of freedom in arm-movement strategies for restoring balance. That is, during locomotion arm movement is relatively unconstrained and, because the arms are not directly interacting with the ground, they are not in a mechanical position to immediately and directly modify stability. Haridas et al. (2006) reported a general facilitation of interlimb reflexes in the arms when the arms were crossed in front of the body during an unstable walking task. This facilitation appeared in several muscles and a general role for interlimb reflexes in corrective responses during locomotion was postulated.

It is possible that the arms have a limited and variable role in perturbations such as tripping or stumble correction unless a stabilizing object (e.g., a handrail) is held; that is, unless the locomotor context is appropriate for functional participation by the arms. Holding an earth-referenced handrail reduces the degrees of freedom in arm movement and provides a fixed object for the arm to brace against. As such, activity in arm muscles can immediately help to mechanically stabilize the body. Earth-referenced rail contact has been shown to dramatically enhance postural stability while standing, even when the force of contact is subthreshold for directly affecting mechanical stability (Lackner et al. 2000, 2001). During walking, the perceived stability that a rail provides has also been suggested to affect responses to destabilizing inputs in leg muscles...
The purpose of this study was to investigate whether reflex pathways are gated differently when an earth-referenced handrail is held. We hypothesized that interlimb reflexes in the arms would be amplified when an earth-referenced arm, enabling the arm to use the rail for support. Conversely, because the arm could take on more of a mechanically supportive role, we predicted that reflex responses in the legs and trunk would decrease in amplitude when rail contact. Furthermore, we predicted that these effects of holding the rail (context effects) would be greatest during the most unstable part of the step cycle (i.e., swing phase) and during more unstable locomotor tasks (such as incline walking and stair climbing, during the threat of tripping is greater than that during level walking). Some portions of the data were previously described in abstract form (Lamont et al. 2002).

METHODS

Subjects and tasks

In all, 19 neurologically intact subjects (8 males and 11 females between 21 and 44 yr of age) participated in the experiments with informed, written consent. All subjects were healthy and free of documented neurological impairment. All experiments were conducted under approved protocols for human subjects at the Universities of Alberta and Victoria and according to the Declaration of Helsinki.

Experiment 1: context effects during three locomotor tasks

This experiment tested the effect on reflex amplitudes of holding a rail during three different locomotor tasks. Nine subjects performed a series of three locomotor tasks: 1) walking on a treadmill (Spirit Manufacturing, Jonesboro, AR) with no incline (LEVEL); 2) walking on an inclined treadmill (INCLINE); and 3) stair climbing on a stepping mill (StepMill 7000PT, StairMaster, Kirkland, WA) (STAIRS). These three tasks were selected because motor patterns on the treadmill and stepping mill are similar to those during the everyday activities of walking and stair climbing. All tasks were performed while holding onto a handrail on the right side. The subjects were instructed to grasp the rail lightly, as they normally would hold a rail during locomotion, and were told not to grip or use the rail for support. The rail was at waist height and was held at a comfortable position for the subjects, slightly in front of the body, and the left arm was allowed to swing normally. The speed of the treadmill was set to 1.1 m/s (~1 step/s) and the level of difficulty on the stepping mill was set to allow subjects to comfortably pace their stepping at one step per second, to closely approximate the same step cycle timing between tasks. The treadmill was inclined to 15° during incline walking and the inclination for the stepping mill was 45° (rise/run for each step = 20.3/20.3 cm). Subjects performed each task for 7 min and were allowed to take short breaks if they felt tired. Each 7-min trial resulted in about 450 steps on the treadmill and 400 steps on the stepping mill.

To determine the effect of holding the rail, these data were compared with recently published data recorded from the same subjects (on the same experimental day) performing the same three tasks, but without holding a handrail (see Lamont and Zehr 2006). In the original experiment, the order of the trials holding and not holding the rail was randomized. Although results from the previous study are not revisited, some of the data are replotted and used for comparison in the present study (Figs. 1 and 2).

Experiment 2: nature of context-dependent effects during incline walking

This experiment tested whether the observed context effects were dependent on holding an earth-referenced rail. An additional six subjects performed incline walking on a treadmill (DESMO-M, Woodway, Waukesha, WI) inclined to 15° during five different rail-holding contexts: 1) not holding a rail with arms moving naturally by sides (NO RAIL); 2) lightly holding a rail (LIGHT HOLD); 3) gripping the rail with the hand (GRIP); 4) leaning on the rail for some body weight support (SUPPORT); and 5) holding onto a hard plastic cylinder that was the same diameter as the rail but not earth-referenced (MOVING). The cylinder weighed 700 g and had a diameter of
7.5 cm and a length of 35 cm. In this last context, the arms were able to move naturally by the sides while holding the freely moving cylinder. The rail or cylinder was held with the right hand while the left arm was allowed to move naturally. The speed of the treadmill was set to 1.1 m/s (pacing /H11061 1 step/s). Each trial lasted between 6 and 7 min ( ~420 steps were obtained) and the order of the trials was randomized.

To rule out the effect of arm position, a final control experiment was performed on an additional four subjects during incline walking. Four contexts were tested: NO RAIL, LIGHT HOLD, RAIL POSITION (subjects held their arm in same position as it was during LIGHT HOLD, without actually holding anything), and BRACE (a brace held the arm in the same position as it was during LIGHT HOLD; subjects did not hold anything). All contexts involved the right arm, whereas the left arm was allowed to move naturally. Similar to the other experiments, the speed of the treadmill was set to 1.1 m/s and each trial lasted between 6 and 7 min. The order of the trials was randomized. Electrogoniometers (Biometrics, Gwent, UK) were placed over the elbow and shoulder joints to measure flexion and extension movements.

Electrical stimulation

The right sural nerve was stimulated just posterior and inferior to the lateral malleolus using a Grass S88 stimulator connected in series with a SIU5 isolation unit and a CCU1 constant-current unit (Grass Instruments, Quincey, MA) (Lamont and Zehr 2006; Zehr et al. 1998). Stimulation was applied to the sural nerve using flexible disposable surface EMG electrodes (experiment 1: Vermont Medical, VT; experiment 2: Thought Technology, Montreal, QC, Canada) with trains of $5 \times 1.0$ ms at 300 Hz at twofold the threshold at which clear and full radiating parasthesia into the lateral foot margin was perceived, as described previously (Lamont and Zehr 2006).

Electromyography (EMG)

Once the skin was cleaned with alcohol, disposable surface electrodes were placed on the skin over muscles in the arms, trunk, and legs. All muscles were recorded ipsilaterally to the site of stimulation (right side), except posterior deltoid, which was recorded bilaterally in experiment 2. For experiment 1, EMG recordings were obtained from all nine subjects for posterior deltoid (PD), erector spinae (ES), rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA), and medial gastrocnemius (MG). For experiment 2, EMG recordings were obtained from all six subjects for flexor carpi radialis (FCR), triceps brachii (TB), anterior deltoid (AD), ipsilateral posterior deltoid (iPD), contralateral posterior deltoid (cPD), erector spinae (ES), and tibialis anterior (TA). In four subjects, recordings were also obtained from MG. In the control experiment testing the effects of arm position, EMG recordings were obtained from four subjects for TB and PD. Ground electrodes were placed over electrically neutral tissue. EMG signals were amplified at $\times 5,000$ and filtered from 100 to 300 Hz (Grass P511, Astro-Med Grass).

Data acquisition and EMG analysis

Data were sampled at 1 kHz with a 12-bit A/D converter connected to a computer running custom-written LabVIEW virtual instruments (National Instruments, Austin, TX). Off-line analysis separated the step cycle into eight equal parts (phases) beginning with the initiation of stance on the right side, which was recorded using custom-made force sensors taped to the insole of the shoes and placed beneath the

FIG. 2. Normalized background EMG and middle latency reflex amplitude during LEVEL, INCLINE, and STAIRS NO RAIL. Values were averaged across all subjects for each task and context (±SE) and normalized to the maximum undisturbed EMG during INCLINE NO RAIL. Background EMG is shown by line plots and middle latency reflex amplitudes are shown in bar plots. Solid line at the bottom of the graphs marks stance phase and the dotted line marks swing. PD, posterior deltoid; ES, erector spinae; RF, rectus femoris; VL, vastus lateralis; BF, biceps femoris; TA, tibialis anterior; MG, medial gastrocnemius.
heel and ball of the foot. The stimulations occurred randomly throughout the step cycle and reflexes were separated into phases according to when the stimulations occurred. EMG data were full-wave rectified and low-pass filtered at 40 Hz with a dual-pass Butterworth filter.

EMG from nonstimulated (control) step cycles was subtracted from that in stimulated cycles to obtain subtracted reflex traces. Reflex traces that occurred within the same phase were averaged together (between 10 and 20 reflexes occurred in each phase for each subject). For more details about the subtraction and averaging of reflexes, refer to Lamont and Zehr (2006) and Haridas and Zehr (2003). Averaged reflexes were considered significant if the peak exceeded a 2SD band above or below the prestimulus mean EMG level. Amplitudes of middle latency reflexes were quantified and averaged across subjects for each task and context. We focused our analysis on the middle latency responses (peak latency ≈ 80–120 ms after stimulation) because these responses tend to be larger and occur most frequently (Baken et al. 2005).

Statistics

The mean amplitudes of all data (reflex and background EMG) were normalized to the maximum background (i.e., nonstimulated) EMG level during INCLINE NO RAIL. Normalization was performed for each subject before averaging the subject data together. Linear regression analysis was used to determine significant relationships between reflex amplitudes and background EMG levels. Other statistical procedures are subsequently described. For all analyses, statistical significance was set to $P < 0.05$, except during post hoc and planned comparison analyses for which the significance level was adjusted according to the number and type of comparisons made.

**EXPERIMENT 1.** In this experiment, we were interested in whether holding a rail affected reflexes across the step cycle (i.e., reflex modulation patterns) during different locomotor tasks. To test the effect of holding the rail, we compared the current data set to the previously published data set without holding a rail (Lamont and Zehr 2006; shown in Fig. 3) by performing a three-way (2 contexts × 3 tasks × 8 phases) repeated-measures ANOVA. Tukey’s HSD test was used for post hoc analysis of context and task main effects and the context × task × phase interactions. To test the hypothesis that the context effect would change with the difficulty of the task, we performed a two-way (3 tasks × 8 phases) repeated-measures ANOVA on data from the three tasks while holding the rail. We predicted effects of holding a rail would be largest during swing phase and thus planned comparisons were performed on the data from each task for phases 5–8.

**EXPERIMENT 2.** To compare the different variations of context to one another, a two-way repeated-measures ANOVA was used (5 contexts × 8 phases). In the control experiment for arm position, a two-way repeated-measures ANOVA was also used (4 contexts × 8 phases). Tukey’s HSD post hoc analysis was performed on significant context main effects and context × phase interactions and planned comparisons were performed on the data from each context for phases 5–8.

**RESULTS**

**Experiment 1: context effects during three locomotor tasks**

Example background EMG and reflex traces from an individual subject for arm (PD), trunk (ES), and leg (TA) muscles...
during the different tasks and contexts are shown in Fig. 1. The middle latency responses are highlighted with rectangles. This subject showed marked facilitatory reflexes in PD during swing phase, which were present only when the rail was held (Fig. 1A). In ES, small decreases in reflex amplitude were noted during swing phase when the rail was held (see Fig. 1B: incline, phase 7 and stairs, phases 7 and 8). Although there were no effects of holding the rail in TA, there was a task effect where the sign of the reflex reversed (became suppressive) during the swing phase of stair climbing, as compared with level and incline walking (i.e., phase 5; see Fig. 1C).

**Background EMG**

Figure 2 shows the mean background EMG amplitude (line plots) during LEVEL, INCLINE, and STAIRS without holding the rail (NO RAIL). These data have been replotted from Lamont and Zehr (2006) to use for comparison with Fig. 3 showing RAIL data. Note that the data in Lamont and Zehr (2006) were normalized to the maximum background EMG during LEVEL NO RAIL, whereas the replotted data in Fig. 3 were normalized to that during INCLINE NO RAIL to facilitate comparisons between data from experiments 1 and 2. Because the task differences in the NO RAIL data have been discussed in the previous publication, they will not be revisited here.

Generally, background muscle activity during the rail holding tasks was similar in the arm muscles, but several differences were noted in the trunk and leg muscles (as indicated in Fig. 3 by the symbols denoting task differences above the line plots). The asterisks above the line plots on Fig. 4 denote whether background EMG amplitude was different when these three tasks were performed while holding a rail compared with when the same tasks were performed without holding a rail (Fig. 3). The greatest number of context differences occurred in PD, with fewer seen in other muscles (ES, BF, TA, MG). In PD, holding the rail caused a general decrease in EMG amplitude during the swing phase (* above line plots in phases 5–8); the magnitude of this decrease in EMG was between 14 and 29% of the value during NO RAIL. During stance, holding a rail caused both increases and decreases in PD EMG amplitude, as compared with NO RAIL (* above line plots in phases...
Middle latency reflex amplitudes

The facilitatory middle latency reflex in PD when holding a rail that was evident in the single-subject data (Fig. 1) can also be seen in the group data (compare PD bar plots in Fig. 2 to those in Fig. 3). This large facilitation was observed only during stance-to-swing transition and swing phase (* below bar plots in phases 5–7; percentage change from NO RAIL was between 356 and 8,547%) and was greatest during stair climbing (main effect for context and task). Also, similar to what was observed in the single-subject data, there was a general decrease in reflex amplitude for ES when the rail was held (Fig. 3; percentage change from NO RAIL was between 48 and 52%). Other differences arising from context were observed in RF, VL, BF, TA, and MG (as noted on Fig. 3).

Similar to single-subject observations, there was a reflex reversal in TA during early swing (i.e., phase 5) where the facilitatory reflex during level and incline walking switched to being suppressive during stair climbing. This reflex reversal was observed regardless of whether the rail was held (see TA bar plots in Figs. 2 and 3). Other significant task differences (Fig. 3) were observed during RAIL contexts at late swing phase in ES (phase 7) and MG (phases 3 and 8).

Experiment 2: origin of context-dependent effects

This experiment was conducted to determine which aspects of holding the rail caused the reflex changes. Five rail-holding contexts were tested during incline walking: NO RAIL, LIGHT HOLD, GRIP, SUPPORT, and MOVING. Incline walking was chosen to be the locomotor task performed throughout this experiment because we observed significant context-dependent reflex modulation, particularly in PD of the arm holding the rail during this task in the earlier experiment.

Background EMG

There was at least one significant difference ascribed to context in the background EMG of all of the upper limb muscles (FCR, TB, AD, iPD, cPD) and the trunk muscle (ES) (see * above the line plots in Fig. 4). The asterisks in Fig. 4 signify that at least one significant difference between contexts was found on post hoc analysis and planned comparisons at that phase. These differences in background EMG are largely consistent with the instructions given to the subjects for each context condition. For example, FCR muscle activity was highest during GRIP and TB muscle activity was highest during SUPPORT. No changes in background EMG were found in the two lower limb muscles (TA, MG); therefore the muscle activity was consistent between different incline walking trials, regardless of the type of rail contact. The precise statistical differences are listed in Table 1.

Middle latency reflex amplitudes

The bar plots in Fig. 4 show middle latency reflex amplitudes across the step cycle for the five rail contexts. Reflexes evoked during NO RAIL and MOVING tended to follow a similar pattern of modulation in most of the muscles. For example, there was no difference in reflex amplitude between NO RAIL and MOVING for TB and iPD, even when the other contexts were quite different. Notice especially the extensive modulation of reflex amplitude in TB during SUPPORT. The middle latency response in this muscle was greatly facilitated during swing phase (* below bar plots in phases 6 and 7) despite the decreasing muscle activity at this time in the step cycle (compare with background EMG line plots). Statistical analyses are summarized in Table 2. There were no significant differences in reflex amplitude in the two lower limb muscles (TA and MG) across all contexts (Fig. 4 and Table 2).

Figure 5 highlights the context differences observed in iPD at the stance-to-swing transition (phase 5) and in TB at the late swing (phase 7). In iPD, reflexes are small and suppressive during NO RAIL and MOVING, but reverses in sign to become facilitatory during LIGHT HOLD, GRIP, and SUPPORT. NO RAIL and MOVING are significantly different from all of the other rail-holding contexts (LIGHT HOLD, GRIP, and SUPPORT). In TB, reflexes are smallest during NO RAIL and MOVING and are largest during SUPPORT.

We performed a control experiment to determine whether the effects of holding an earth-referenced rail could have been attributable to arm position. Four additional contexts were tested and compared during incline walking: NO RAIL, LIGHT HOLD, RAIL POSITION (i.e., subjects held the arm in the same position as it was during LIGHT HOLD, except without holding anything), and BRACE (i.e., a brace held the arm in the same position as it was during LIGHT HOLD;
The amplitudes of the majority of reflexes were not directly related to the background muscle activity.

**DISCUSSION**

There are two main new findings in this study. First, holding an earth-referenced rail altered cutaneous reflex amplitudes in muscles across the entire body. This effect of the rail was different depending on the walking task being performed, suggesting that transmission in segmental and interlimb reflex pathways is influenced by the stability (i.e., context) of each task, as conveyed by holding a rail, while also being subject to specific gating according to the locomotor task. Second, holding the rail amplified reflexes in muscles that were functionally able to make use of the rail to restore balance. Differences arising from holding the rail were observed only when the rail was earth-referenced and were not present when subjects were holding a freely moving cylinder (moving rail). These differences were also not present when the arm was fixed or held in the same position as it was during rail-holding, without actually holding a rail. This suggests that these reflex changes may contribute to relevant mechanical stabilization of the body during locomotion.

**Context-dependent modulation**

Holding a rail during the three locomotor tasks altered cutaneous reflex amplitudes (see Figs. 1, 2, and 3) most dramatically in the arm holding the rail (PD). The effects were smaller in the trunk (ES) and leg muscles (RF, BF, TA, and MG). Interestingly, the independent expression of reflex control for the arms and legs is similar to the independence of upper and lower body movement following galvanic vestibular stimulation during walking (Bent et al. 2004).

The middle latency reflexes in ES tended to diminish in amplitude while holding the rail, particularly during late swing and the swing-to-stance transition (phases 7 and 8). The trunk muscles typically play a role in restricting excessive trunk movements during locomotion, thus stabilizing the body (Thorstensson et al. 1982). We suggest that when the rail is held, reflex amplitudes decrease because the arm takes on some of the role of stabilizing the body. This could reflect the ability of the nervous system to gate reflexes such that the most effective response to a disturbance results, taking into account the stability of each context.

**TABLE 2. Summary of results from post hoc analyses and planned comparisons for middle latency reflex amplitude during five different contexts**

<table>
<thead>
<tr>
<th>Context</th>
<th>No Rail</th>
<th>Light Hold</th>
<th>Grip</th>
<th>Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIGHT HOLD</td>
<td>TB (5–8)</td>
<td>iPD (3–5)</td>
<td>cPD (7, 8)</td>
<td>TA (8)</td>
</tr>
<tr>
<td>GRIP</td>
<td>iPD (4, 5)</td>
<td>cPD (8)</td>
<td>TA (8)</td>
<td>NS</td>
</tr>
<tr>
<td>SUPPORT</td>
<td>TB (6, 7)</td>
<td>iPD (4–6)</td>
<td>iPD (7)</td>
<td>iPD (6, 7)</td>
</tr>
<tr>
<td>MOVING</td>
<td>cPD (8)</td>
<td>TB (6–8)</td>
<td>ES (8)</td>
<td>TB (6, 7)</td>
</tr>
</tbody>
</table>

Statistical differences are noted as in Table 1. For example, NO RAIL is different from SUPPORT for TB (phases 6 and 7) and iPD (phases 4–6). NS indicates no significant differences.

Subjects did not hold onto anything. During LIGHT HOLD, RAIL POSITION, and BRACE, the position of the arm was similar (see elbow and shoulder angle plots, Fig. 6). However, middle latency reflexes in TB and PD were still facilitated more in LIGHT RAIL than in any of the other contexts (bar plots, Fig. 6; asterisks below bar plots denote where LIGHT RAIL was different from at least one of the other contexts). Notice that the significant differences in middle latency reflex amplitude resulting from holding an earth-referenced rail occurred when there were no significant differences in background EMG (compare asterisks above line plots for background EMG to asterisks below bar plots for middle latency reflexes).

As an additional control to ensure that the differences in reflex modulation were not largely explained by fluctuations in background EMG, we tested the correlations between reflex amplitude and background EMG (results shown in Table 3). There were only two instances where the reflex amplitude was negatively correlated with background EMG during the Locomotion. There were two main new findings in this study. First, holding an earth-referenced rail altered cutaneous reflex amplitudes in muscles across the entire body. This effect of the rail was different depending on the walking task being performed, suggesting that transmission in segmental and interlimb reflex pathways is influenced by the stability (i.e., context) of each task, as conveyed by holding a rail, while also being subject to specific gating according to the locomotor task. Second, holding the rail amplified reflexes in muscles that were functionally able to make use of the rail to restore balance. Differences arising from holding the rail were observed only when the rail was earth-referenced and were not present when subjects were holding a freely moving cylinder (moving rail). These differences were also not present when the arm was fixed or held in the same position as it was during rail-holding, without actually holding a rail. This suggests that these reflex changes may contribute to relevant mechanical stabilization of the body during locomotion.

**FIG. 5.** Highlighted middle latency reflexes in iPD and TB during different rail contexts. This figure highlights the specific responses in iPD at the stance-to-swing transition (phase 5, left plot) and in TB at late swing (phase 7, right plot). Along the x-axis, SUP = SUPPORT and MOV = MOVING. Statistical differences are shown by brackets. For example, for iPD at phase 5 (stance-to-swing), NO RAIL and MOVING are different from all of the other contexts (LIGHT HOLD, GRIP, and SUPPORT). For TB at phase 7 (late swing), reflexes during SUPPORT are significantly larger than in any other context. Additionally, reflexes are also larger during LIGHT HOLD than during NO RAIL or MOVING. These statistical differences can also be determined by referring to Table 2 (see iPD phase 5 and TB phase 7).
Reflexes in the lower limbs exhibited variable context effects: sometimes reflexes were facilitated (i.e., larger in amplitude) when the rail was used, sometimes they were suppressed (i.e., smaller in amplitude), and sometimes reflex reversals were observed (i.e., a change from a facilitatory reflex to a suppressive one). Similarly, Rietdyk and Patla (1998) also found that rail contact had a variable effect on reflex responses in the legs. They suggested that the changes in reflex gain produced an optimal recovery strategy, in which unnecessary responses were minimized and more relevant responses were enhanced. In the current study, generally facilitation tended to decrease and suppression to increase when the rail was held (i.e., facilitatory reflexes were smaller and suppressive reflexes were larger). Both of these observations yield the same overall trend in reducing motor activity and could reflect the phenomenon reported by Misiaszek and Krauss (2005) that responses to disturbances in leg muscles were smaller during more stable locomotor tasks. Another interesting point to note with regard to leg reflexes is that the reflex reversal in TA at the stance-to-swing transition (i.e., phase 5) during stair climbing (no rail) that was reported by Lamont and Zehr (2006; data shown in Fig. 2) was still present when the rail was held (see Fig. 3).

The large increase or facilitation of PD reflex amplitude may reflect a “switch” in the potential function of the arm and yield access to relevant interlimb reflex pathways. Without external support from the rail, the arms can be observed to elevate (to shift the center of mass forward) or move toward a rail in response to a perturbation (Marigold et al. 2003; McIlroy and Maki 1995). However, when the rail is held, it offers the arm a much larger mechanical role in restoring balance after a disturbance. For example, if tripping were to occur, the arm could be used to support the body against the rail and prevent falling; specifically, PD may abduct the arm to better position it to use the rail for support. The reflexes in PD may be gated to reflect this functional role, thus enabling this muscle to have a role in the corrective response. The response in this muscle is enhanced only when the arm can actually aid in restoring balance and this facilitation is observed only near the stance-to-swing transition and swing phase, when a perturbation is most likely to have a destabilizing effect. Also, further facilitation is observed as subjects perform tasks during which tripping is more likely (e.g., stair climbing as opposed to level walking). This corroborates the findings of Haridas et al. (2006), who also found that interlimb reflexes were scaled to the degree of postural threat and were also affected by the arms being positioned in front of the chest, where they were constrained from participating in corrective responses. That is, having the arms crossed in front of the body limits the ability to use arm motion in corrective responses.

In the second experiment using five variations of rail holding during incline walking, a similar facilitatory response in PD was observed when the rail was held with this arm (regardless of whether it was a light, gripping, or supporting hold), but only if the rail was earth-referenced. When subjects held a freely moving cylinder, reflex modulation followed a similar pattern to when they were not holding a rail at all (see iPD; Figs. 4 and 5). Furthermore, when subjects held their arm in the same position as they would when holding the rail, it offered the arm a much larger mechanical role in restoring balance after a disturbance. For example, if tripping were to occur, the arm could be used to support the body against the rail and prevent falling; specifically, PD may abduct the arm to better position it to use the rail for support. The reflexes in PD may be gated to reflect this functional role, thus enabling this muscle to have a role in the corrective response. The response in this muscle is enhanced only when the arm can actually aid in restoring balance and this facilitation is observed only near the stance-to-swing transition and swing phase, when a perturbation is most likely to have a destabilizing effect. Also, further facilitation is observed as subjects perform tasks during which tripping is more likely (e.g., stair climbing as opposed to level walking). This corroborates the findings of Haridas et al. (2006), who also found that interlimb reflexes were scaled to the degree of postural threat and were also affected by the arms being positioned in front of the chest, where they were constrained from participating in corrective responses. That is, having the arms crossed in front of the body limits the ability to use arm motion in corrective responses.

FIG. 6. Effects of arm position context on background EMG and middle latency reflex amplitude during incline walking. Values were averaged across all subjects (n = 4) for each context (±SE) and normalized to the peak undisturbed EMG during the no rail context. Background EMG is shown by line plots and middle latency reflex amplitude is shown by bar plots. Significant context main effects (context) are indicated by text (top left for background EMG; bottom left for middle latency reflexes). Asterisks above the lines (background EMG) and below the bars (middle latency reflexes) indicate that LIGHT HOLD is different from at least one of the other contexts at that phase in the step cycle. Elbow and shoulder angles across the step cycle for each context are shown in the bottom plots. Solid line at the bottom of the graph marks stance phase and the dotted line marks swing. TB, triceps brachii; PD, posterior deltoid.
response to perturbations. In this example, IF the hand is in contact with an earth-referenced support THEN interlimb reflex facilitation in PD is present.

Triceps brachii (TB) also exhibited a facilitation of the middle latency response when an earth-referenced rail was held (Figs. 4, 5, and 6). Similar to ipsilateral PD, reflex modulation was similar between the no rail and moving rail conditions, and the reflexes were not facilitated when the arm was simply held in the rail position, indicating that facilitation did not occur unless subjects were holding an earth-referenced object. In contrast to PD, the response in TB when the subjects were supporting themselves with the rail was further amplified than in any of the other fixed rail conditions. Note that the amplitude of muscle activity was increased throughout the step cycle in any of the other fixed rail conditions. Note that the amplitude of muscle activity was increasing (activity was decreasing). The reflex may be gated during the stance phase because exerting more force on the rail by an increased TB contraction is not needed during this relatively stable phase of the step cycle. During the more unstable swing phase, gating of the reflexes may be released to allow for appropriate balance-compensation reactions. Therefore the functional set may be gated not only to reflect the availability of the rail, but also to adjust for the relative contribution of each muscle involved in performing the task.

We speculate that the observed context-dependent modulation of interlimb reflexes reflects the functional application of the phenomenon studied extensively by Lackner’s group. It was clearly shown that increased postural sway, which occurred when eyes were closed, was effectively nullified by contact on the fingertips even at extremely low force levels (i.e., <1 N and below levels for mechanical support) (Holden et al. 1994; Jeka and Lackner 1994). Furthermore, it was shown that even 5–10 g of force can be effective and that the best effects are seen when the reference point is stationary (Lackner et al. 2001). We suggest that our data (where the largest effects were seen only in the earth-referenced context) extend these observations to integrated corrective responses during walking (also see Rietdyk and Patla 1998; Schneider and Capaday 2003).

Another possibility is that holding the rail represents a new motor task or program and the alterations in reflexes may be indicative of task-dependent, rather than context-dependent, differences in neural control. This seems unlikely because the facilitation in TB and PD reflex pathways was not observed when the arm was in the “rail-holding” position without holding anything. We believe it to be more likely that the observed changes associated with holding the rail were related to the stability provided by the rail during locomotion. This explanation could account for why reflexes in PD were amplified the most during the task where tripping was most likely—stair climbing, when the rail was held. In contrast, following the hypothesis that the observed changes were reflective of a change in the motor program, we would be unable to predict this specific response. Further to this point, Schneider and Capaday (2003) found that during an unfamiliar walking task (backward walking) there was an unexpectedly large H-reflex that occurred in midswing that was not present during forward walking. This large H-reflex was diminished immediately on rail contact and was also similarly diminished over time with practice of backward walking without rail contact. The authors concluded that this reflex was related to task uncertainties during backward walking and that the reduction in the reflex that occurred with rail contact or with practice of the task was likely a result of the increased postural confidence (Schneider and Capaday 2003). We suggest that the changes in cutaneous reflexes associated with rail contact in the present study are also related to alterations in stability and postural confidence.

### Functional relevance

The facilitation of interlimb responses in TB and PD when an earth-referenced rail is held suggests that neural pathways to
these muscles are gated to incorporate the rail into the automatic recovery strategy. That is, these enhanced reflexes may have a role in stumble correction, making use of the rail to restore stability. Although this is likely of benefit to most people, it may be detrimental to those who rely on earth-referenced assistive devices such as a cane or walker. For instance, Batini et al. (2004) showed that when a cane was held during walking with large perturbations, subjects tended to keep holding onto the cane as they were falling instead of dropping it to grab onto a more stable object such as a rail. If interlimb reflexes are selectively gated to make use of an object that is perceived to provide stability, this conceivably may lead to an overreliance on canes or walkers. This is an area of functional application that requires further study.

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