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Out-of-plane trunk movements and trunk muscle activity after a trip during walking

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Abstract Tripping during gait occurs frequently. A successful balance recovery implies that the forward body rotation is sufficiently reduced. In view of this, adequate control of the trunk momentum is important, as the trunk has a high inertia. The aim of this study was to establish out-of-plane trunk movements after a trip and to determine trunk muscle responses. Ten male volunteers repeatedly walked over a platform in which 21 obstacles were hidden. Each subject was tripped over one of these obstacles at mid-swing of the left foot in at least five trials. Kinematics, dynamics, and muscle activity of the main trunk muscles were measured. After a trip, an increase in trunk flexion was observed (peak flexion 37°). In addition, considerable movements outside the sagittal plane (up to 20°) occurred. Already before landing of the blocked foot, the trunk forward bending movement was reduced, while trunk torsion and lateral rotation were still increasing. Fast responses were seen in both abdominal and back muscles, indicating stiffening of the trunk. These muscle responses preceded the mechanical trunk disturbances, which implies that these responses were triggered by other mechanisms (such as afferent signals from the extremities) rather than a simple stretch reflex. A second burst of predominantly trunk muscle extensor activity was seen at landing, suggesting specific anticipation of the trunk muscles to minimize trunk movements due to landing. In conclusion, despite large movements outside the sagittal plane, it appears that trunk muscle responses to trips are aspecific and especially aimed at minimizing trunk forward bending.

Keywords Tripping · Trunk movements · Muscle activity · Trunk stability · Postural control

Introduction

Falls are a major cause of health problems, especially among the elderly population, and are a leading cause of injury-related deaths (Murphy 2000). The medical expenses related to falls are high, mostly due to serious fall-related injuries such as hip and elbow fractures (Berg et al. 1997). Balance control has been extensively studied, especially during stance. With age, clear changes in the control of stance have been shown, including increase of body sway and decreased control of lateral stability (Maki and McIlroy 1996). It was found that adequate control of the trunk movements was necessary to maintain balance during stance when perturbations were applied (Carpenter et al. 1999; Allum et al. 2002; Gruneberg et al. 2004). In elderly subjects, trunk control was decreased (Allum et al. 2002), which could partly explain age-related changes in balance control.

Although many studies have investigated balance control in response to perturbations during (quasi)static tasks, most falls occur during dynamic activities such as walking (Tinetti et al. 1988). Unfortunately, perturbations during quiet stance are not comparable with perturbations during walking. The aim of balance control during walking is different from that during a quasistatic posture. For example, during walking, the centre of mass is usually outside the base of support (Winter 1995), whereas during quiet stance the centre of mass has to fall within the base of support. Consequently, mechanical parameters in relation to movement, such as linear and angular momentum, must be controlled in walking in addition to the position of the centre of mass relative to the base of support (Hof et al. 2005). Hence, postural responses to disturbances during quasistatic stance are not predictive for those that occur during disturbed locomotion.

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Recent studies have examined balance control after perturbations during walking, such as tripping (Grabiner et al. 1993, 1996; Eng et al. 1994; Schillings et al. 2000; Pijnappels et al. 2005). To recover successfully from a trip, the increase in forward rotation, which the body gets from impact with the obstacle, must be reduced. Because the trunk has a high inertia, adequate control of the trunk momentum appears to be important during walking. Grabiner et al. (1993) suggested that recovery from a stumble depends on the ability to control trunk movement. After a trip, the trunk was found to bend forward, up to a flexion angle of 30° (Grabiner et al. 1993, 1996; Eng et al. 1994; Pavol et al. 1999). Unfortunately, movements outside the sagittal plane after a trip were not described. Application of the impact forces due to collision with the obstacle is likely to be lateral to the lumbar spine joint. Consequently, trunk torsion and lateral rotation may occur after a trip. Because control of lateral stability is an indicator of the likelihood of a fall in the elderly (Stel et al. 2003), in this experiment we studied the trunk movements after a trip in three dimensions.

Unexpected trunk movements are often accompanied by coactivation of the trunk muscles, probably to secure the stability of the spine (Thomas et al. 1998; Krajcarski et al. 1999; van der Burg et al. 2000). Such coactivation has been seen after a slip (Tang and Woollacott 1998). However, after a perturbation during stance, trunk muscle activation specific to the direction of the perturbation of trunk posture has been shown (Carpenter et al. 1999). It is unclear whether coactivation or a more perturbation-specific trunk muscle response would occur after a trip. Fast activation of the erector spinae muscles, with latencies of 60–90 ms, were seen in response to a trip (Eng et al. 1994). To our knowledge, no studies describing both abdominal and back muscular responses after a trip have been published yet.

The first aim of this study was to assess the trunk movements outside the sagittal plane after a trip. The second aim was to describe the direction specificity of the trunk muscle responses and to relate them to the observed trunk movements. In addition, the latencies of the trunk muscles were determined to learn what triggered these muscular responses. We hypothesized that substantial trunk flexion as well as lateral rotation would occur in response to a trip. It is unclear whether coactivation or a more perturbation-specific trunk muscle response would occur after a trip.

Methods

Ten men, aged 42 (SD 3.7) years, voluntarily participated in this study. They were informed of the research procedures before they gave informed consent, in accordance with the ethical standards of the Declaration of Helsinki. The subjects were instructed to walk at a self-selected velocity over a 12×2.5-m walkway. In the walkway, a force platform was mounted, which was of similar colour as the walkway in order to obscure it from sight.

Fourteen obstacles 15 cm high were hidden at the left side and seven obstacles were hidden at the right side of the walkway, over a total distance of 1.5 m (see Fig. 1). In about eight of the 70 trials, one of the obstacles suddenly popped up to catch the swing leg of the subjects. At the start of each trial, the subjects did not know whether or where an obstacle would appear. A trip was initiated at mid-swing. Typically after a trip at mid-swing, subjects will perform an elevating strategy; that is, the obstructed limb is lifted over the obstacle (Schillings et al. 2000). In this study, all subjects performed an elevating strategy in all but three trials, in which a lowering strategy was seen. These three trials were discarded for further analysis. A full-body safety harness, worn by the subjects to prevent falling on the floor, was attached to a coupling that moved along a track anchored to the ceiling above the walkway. A more detailed description of the experimental set-up has previously been given by Pijnappels et al. (2004). It has been shown that in this set-up, anticipation of a possible trip only slightly moderates the walking pattern (Pijnappels et al. 2001). These changes are so small in magnitude that they were not expected to alter the probability of tripping or the recovery reactions after tripping.

Kinematic data were collected at a frequency of 100 Hz using four Optotrak camera arrays (Northern Digital). Eight LEDs were placed bilaterally at the joints of the leg. For studying three-dimensional movements of the upper body, the pelvis and trunk segment were recorded using a brace to which three LEDs were attached. We recorded the position of the markers of the braces as well as the markers on anatomical landmarks to allow reconstruction of the anatomical axis system at each instant in time. To describe the segment angles of the trunk and the pelvis, Euler angles were determined in the following sequence: sagittal (forward rotation),

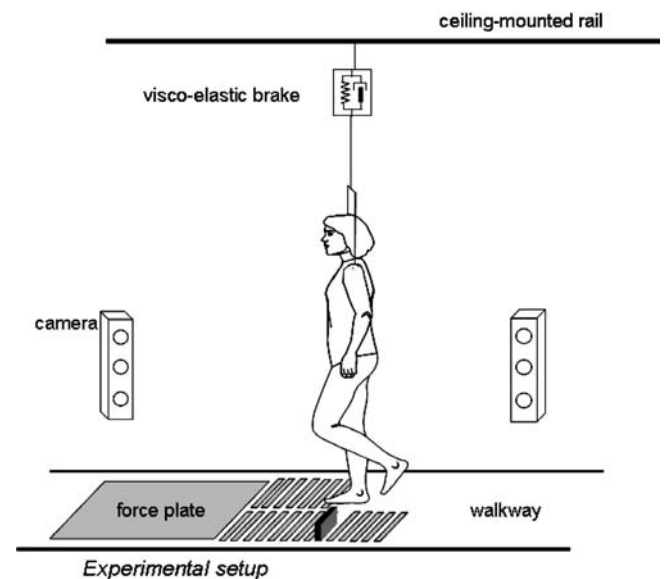


Fig. 1 Schematic diagram of the experimental set-up from a side view

frontal (lateral rotation), and transversal (torsion). Forward rotation, left torsion, and right lateral rotation were defined as positive. To be able to relate the trunk movements to trunk muscle responses, the lumbar spine angle, defined as the angle of the trunk relative to the pelvis, was calculated.

On both sides of the body, the electromyographic (EMG) activity of five main trunk muscles was recorded by means of disposable EMG electrodes (Ag/AgCl) with a centre-to-centre spacing of 2.5 cm. The EMG signals were recorded from the erector spinae muscles at the level of L1 and T9, the rectus abdominus, and the anterior external and internal oblique muscles. All trunk muscles were monitored at positions described in van der Burg et al. (2003). The EMG signals were amplified 20 times (Porti-17, Twente Medical Systems), band-pass filtered (10–400 Hz), sampled (1,600 Hz), and stored on disk with a 22-bit resolution. The signals were whitened (5th order; Clancy et al. 2002) to reduce the influence of tissue filtering and movement artefacts, Hilbert-transformed, rectified, and finally low-pass filtered (5th-order Savitzky-Golay filter). This filtering method smoothes the signal but preserves sudden activity onset without producing a phase lag. For comparison of muscle activity among subjects, the EMG signals of the trunk muscles were normalized to the maximum value per muscle of seven tests of maximal isometric contractions, as described by McGill (1991). Each of these tests was repeated three times.

Online kinematic data of toe markers were used to calculate when and which of the spring-loaded obstacles had to appear to initiate a trip at mid-swing of the left foot. First, the computer calculated which of the 14 obstacles at the left side of the walkway was the closest to the MTP5 marker of the right foot. Then the timing of the release of the obstacle was calculated, based on the subject's step length and velocity. Because the total upward movement of the obstacle took 100 ms, the computer calculated the timing of the release such that the impact with the obstacle was within 100–200 ms after the start of the release of the obstacle. Heel strike and toe-off and obstacle contact were detected based on kinematic data (Pijnappels et al. 2001). To determine obstacle contact, the anteroposterior acceleration of the obstacle was measured. The landing of the blocked foot after the trip was determined by an increase in ground reaction force measured by a custom-made strain gauge force plate (1×1 m).

To determine the onsets of muscle responses, the EMG data of four undisturbed walking trials of each subject were averaged and subtracted from the EMG time series of the individual tripping trials. The resulting signals were analysed by means of a dynamic process model in combination with statistically optimal change detection, as described by Staude and Wolf (1999). This method searches for changes in the EMG sequence by use of the likelihood ratios over small (50 ms) time windows over the first 200 ms after trip initiation. The same procedure was used to determine the onset of L5S1

angular acceleration after a trip. The analysis focuses on the positioning phase, which is initiated at the instant the trip occurs and ends at the instant the blocked foot contacts the ground (Grabiner et al. 1996).

Differences in the onset of activity for each muscle were tested in a multivariate analysis of variance (ANOVA). Post-hoc paired *t*-tests were performed to test the onset differences. To circumvent the problem of cross-talk in interpreting the amplitudes of surface EMG (van Dieen and de Looze 1999), the muscles were grouped in four groups according to their mechanical function: left and right extensors and flexors. To determine the muscle activity in response to the collision with the obstacle, the mean amplitudes were calculated for a period of 120 ms after the trip initiation. The amplitudes of the four muscle groups were tested with an ANOVA. The movements in the sagittal, frontal, and transversal planes of the trunk were tested with *t*-tests to determine whether they were different from normal walking movements. Effects were considered to be significant at $p < 0.05$.

Results

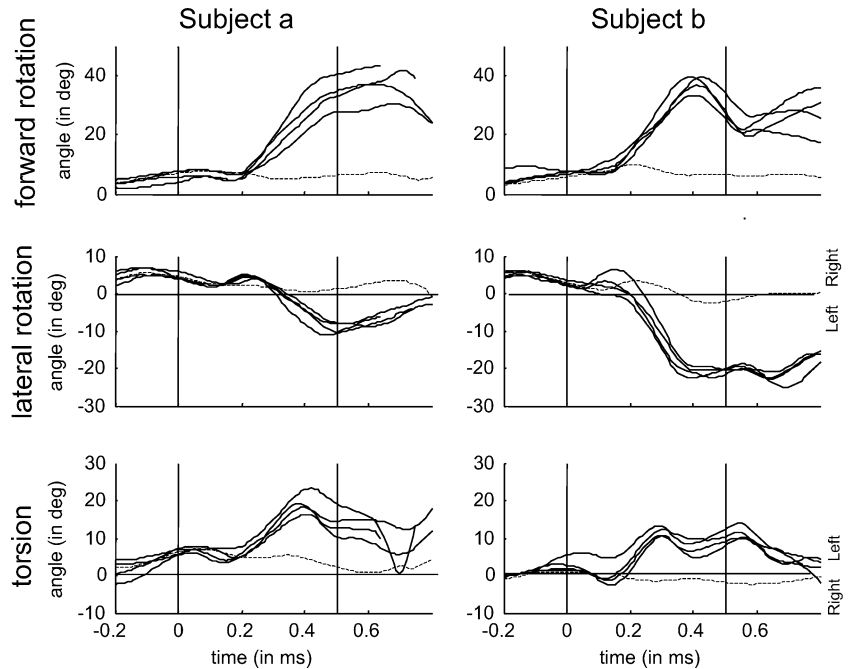
The average walking velocity was 1.58 m/s (SD 0.23 m/s). None of the subjects fell after he was tripped. The foot hit the obstacle on average 200 ms (SD 28 ms) after toe-off. The duration of the total swing phase (from toe-off to heel strike) was 710 ms (SD 63 ms) compared with 470 ms (SD 43 ms) in walking. This indicates that the positioning phase had an average duration of 510 ms (710–200 ms).

Trunk angular displacements were increased because of the impact with the obstacle. The maximum trunk angles were increased significantly not only in the sagittal plane but also in the transversal and frontal planes (trunk forward rotation: 37°[SD 13°], lateral rotation 10°[SD 13°], torsion 16° [SD 12°], $p < 0.001$; see Fig. 2). The lumbar spine angular acceleration, independent of the plane, started to deviate from that in normal walking 122 ms (SD 20 ms) after the initiation of the trip.

In most (73%) trips, the flexion movement of the L5S1 joint due to impact with the obstacle was reduced before the blocked foot landed on the ground, as was indicated by a negative or zero joint angular flexion velocity at landing. Compared with the flexion movement, the trunk deviations outside the sagittal plane were less well counteracted during the positioning phase: In only 45% of all trips was the rotation velocity (transversal plane) zero or negative at landing, and in only 35% of the trips was the lateral rotation velocity (frontal plane) zero or negative.

After a trip, rapid responses of both the back and abdominal muscles (60–80 ms) were seen (Figs. 3 and 4). Note that these responses occurred even before deviations in lumbar spine accelerations appeared. The onsets of the EMG responses of the abdominal muscles were slightly, but significantly, earlier than in the back

Fig. 2 Trunk segment angles for two typical subjects for four tripping trials (*solid lines*) and the averaged walking trial (*dashed line*). Subject A is an example of a subject who was successful in counteracting the perturbation to the trunk movement in the positioning phase. Subject B is one of the subjects who was less successful in counteracting the perturbation to the trunk movements in the positioning phase. The *vertical lines* indicate trip initiation and landing of the blocked foot



muscles (63 vs. 74 ms, respectively, $p < 0.001$). In both the internal and the external oblique muscles, the onset at the left side of the body was significantly earlier than at the right side of the body (internal oblique $p < 0.001$, external oblique $p = 0.034$). During the first 120 ms after a trip, especially the muscles at the left side of the trunk were activated. The mean amplitudes of the left extensor and flexor muscles were significantly higher than the amplitudes of the right muscles after the trip ($p < 0.001$).

A second burst of EMG activity was seen when the blocked foot landed at the surface (Fig. 4). The timing of these bursts of muscle activity could not be determined reliably because of overlap with preceding bursts. To determine the directional specificity of these bursts, the mean amplitudes of the four muscle groups for 50 ms before landing were calculated. A repeated measure ANOVA showed that the amplitudes of the trunk

extensor muscles were significantly higher than the amplitudes of the flexor muscles ($p = 0.006$).

Discussion

The first purpose of this study was to assess trunk movements and trunk muscle activity after a trip. Collision with the obstacle increased the trunk angular deviation in all planes. The maximum trunk forward

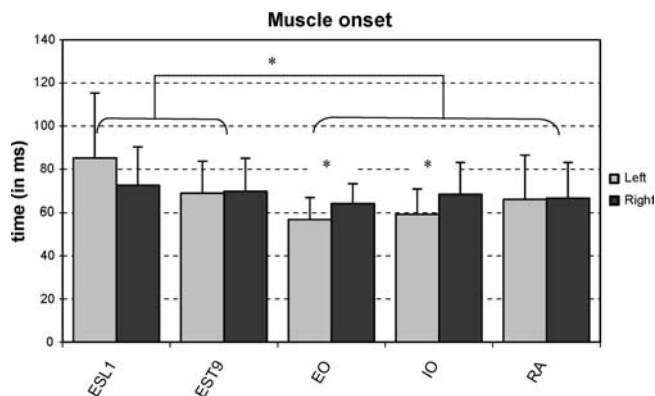


Fig. 3 The onset of trunk muscle activity after a trip. The electromyographic responses of the abdominal muscles occurred significantly earlier than in the back muscles. In the oblique muscles, the muscle onset at the left side of the body was significantly earlier than at the right side of the body

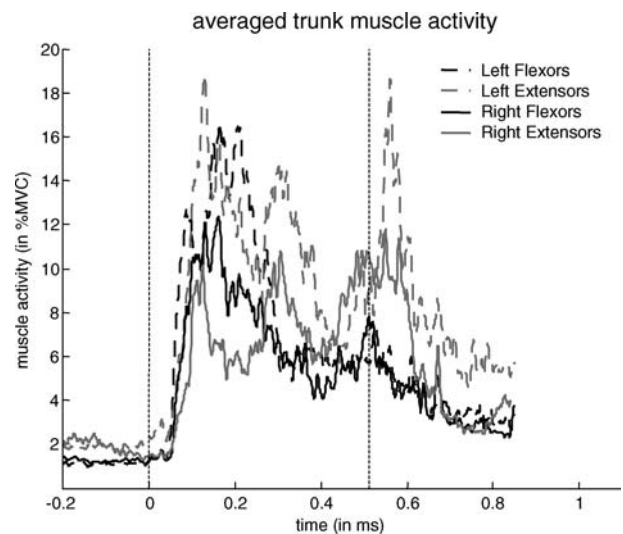


Fig. 4 Averaged trunk muscle activity of all subjects for the four muscle groups. The flexor muscles are plotted in *black lines*, and the extensor muscles are plotted in *grey lines*. The left muscles are represented with *dashed lines*, and the right muscles are represented with *solid lines*. The *vertical lines* indicate trip initiation and landing of the blocked foot. In response to a trip, both back and abdominal muscles were activated. At landing, a second burst of back muscle activity was seen

rotation angle (average 37°) in the present study was comparable to the maximum angle (average 34°) found by Grabiner et al. (1996). In addition, the deviations outside the sagittal plane were considerable. The maximum trunk torsion was almost 20°. Consequently, when studying tripping reactions only in two dimensions, as is common in the published tripping studies, misinterpretation of the data is possible. For example, based on only the flexion angles, the perturbation of the trunk seemed to be counteracted at landing, while the present study showed that this is not the case when the out-of-plane movements were taken into account.

In contrast to the reduction of the forward rotation before landing, incomplete counteraction of movements outside the sagittal plane was seen, likely because lateral movements require a more complex coordination of muscle responses in the left and right side of the body (Carpenter et al. 1999). For example, no single trunk muscle exists that can generate a pure lateral bending moment. The reduced control of the trunk outside the sagittal plane may predispose an individual to lateral falls, which are commonly associated with hip fractures in older adults (Nevitt and Cummings 1993). It can be questioned whether such large movements outside the sagittal plane would also be seen with people younger than the middle-aged men who participated in our study. Allum et al. (2002) showed that with aging, trunk control during stance changed dramatically, especially in the frontal plane. Even in middle-aged subjects, a decrease in trunk control was seen compared with young subjects. Additional tripping studies are required to discover whether similar age-effects on trunk movements can be seen as after balance perturbations during walking.

Specificity of trunk muscle responses

The second purpose of this study was to describe the abdominal and back muscular responses and to relate them to the observed trunk movements. Previous work on balance corrections has shown directionally specific response of the trunk muscles following a perturbation during stance (Carpenter et al. 1999; Gruneberg et al. 2004). In the present study, differences in muscle onsets were found, suggesting a directionally specific response following a perturbation during locomotion as well. However, all abdominal muscles were activated earlier than the back muscles. This abdominal muscle activity counteracts trunk extension and thus appears not to be functional to reduce the flexion of the trunk due to impact with the obstacle. Moreover, the first 120 ms after a trip, the trunk muscles at the left side were especially activated. This is probably not an adequate response, as the left leg had to be lifted over the obstacle. Activation of trunk muscle at the right side facilitates lifting the left leg by bringing the trunk mass over the right stance leg, in contrast to activation of the left trunk muscles. Nevertheless, the trunk muscle activity was sufficient to especially reduce trunk flexion velocity before landing. This may be

due to the stiffening of the trunk during the positioning phase that is caused by activation of both back and abdominal muscles. Similar results were found after a slip during walking (Tang and Woollacott 1998; Tang et al. 1998). A stiff lumbar spine may help to maintain the trunk's alignment above the pelvis and thus, provided that the hip is extended, counteract the forward rotation of the body. Moreover, joint stiffness will immediately provide a torque opposing the change in joint angle due to force-length velocity characteristics of muscles. In tripping, this joint stiffness will cause an extension torque around the lumbar spine, which is required for a successful recovery from a trip (Pijnappels et al. 2005).

The second burst of EMG activity, which was seen at the end of the positioning phase, may indicate anticipatory activation preparing for the landing of the blocked foot on the surface. Landing of the foot on the surface will cause a second perturbation to the trunk movement and is likely to generate a flexion moment on the trunk. In contrast to the first perturbation (collision with the obstacle), this second perturbation is expected and can thus be anticipated. Indeed, the trunk muscles were activated before the blocked foot landed on the surface; this activity can thus be called anticipatory. This muscle activity appeared to be directionally specific because the extensor muscles, which can counteract the flexion moment, were especially activated. Directionally specific anticipation was also found in other studies in which trunk perturbations were applied expectedly (van Dieen and de Looze 1999; Hodges et al. 2000). So a specific muscle activity pattern was seen at landing, whereas an aspecific stiffening response was seen after collision with the obstacle.

Possible triggering mechanisms

Rapid responses, with latencies of 60–80 ms, were seen in trunk muscles, suggesting that the responses are highly automated. These responses were as early as the muscle responses in the lower limbs after a trip, both for the blocked limb as well as for the contralateral limb (Eng et al. 1994; Schillings et al. 1996; Pijnappels et al. 2005). Tang et al. (1998) found longer onset latencies for trunk muscles (120–190 ms) after a slip. In that study, fast activation of trunk muscles to maintain trunk balance might not be necessary, as the slips led to a relatively small perturbation to the trunk (6°) compared with our experiment.

Recently, it has been suggested that especially the trunk and hip movements provide the primary trigger signal for balance-correcting muscle responses (Allum et al. 1998; Carpenter et al. 1999). However, in our study, the trunk muscle responses preceded the mechanical disturbances of the trunk. Hence, it is unlikely that the trunk responses were generated by simple segmental reflexes that resulted from a mechanical disturbance at the trunk. It appears that other mechanisms are responsible for triggering the responses, such as

movements of the extremities or stimulation of the vestibular apparatus, or the responses can be learned responses. It is not expected that the contribution of the vestibular afferents was large during tripping, as vestibular responses have much smaller amplitudes than somatosensory responses (Horstmann and Dietz 1988). It is neither expected that the fast muscle responses were learned responses developed in the course of the experiment, since the first and the later muscle responses were very similar. Therefore, it seems most probable that the responses were triggered by information from the extremities, such as cutaneous information from the blocked leg. Similarly, Hodges et al. (2001) showed that fast trunk muscle responses could be mediated directly by afferent input from the upper extremities.

Conclusion

After tripping, large trunk movements were seen, both in and outside the sagittal plane. Two bursts of trunk muscle activity were seen in response to tripping. During the positioning phase, the trunk muscles co-contracted, which reduced or even reversed the trunk flexion movement. Before landing, a second burst of trunk muscle activity was seen, the pattern of which suggests specific anticipation preparing for landing of the blocked foot. Both bursts of muscle responses appeared to be especially effective in minimizing trunk forward bending, despite large movements outside the sagittal plane.

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