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RESEARCH ARTICLE

Armed against falls: the contribution of arm movements to balance recovery after tripping

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Abstract Arm movements after perturbations like tripping over an obstacle have been suggested to be aspecific startle responses, serve a protective function or contribute to balance recovery. This study aimed at determining if and how arm movements play a functional role in balance recovery after a perturbation. We tripped young subjects using an obstacle that suddenly appeared from the floor at exactly mid-swing. We measured arm muscle EMG, quantified body rotations after tripping, and established the effects of arm movements by calculating how the body would have rotated without arms. Strong asymmetric shoulder muscle responses were observed within 100 ms after trip initiation. Significantly faster and larger responses were found in the contralateral arm abductors on the non-tripped (right) side. Mean amplitudes were larger in the ipsilateral retroflexors and contralateral anteflexors. The resulting asymmetric arm movements had a small effect on body rotation in the sagittal and frontal planes, but substantially affected the body orientation in the transverse plane. With the enlargement of the ongoing arm swing, the arms contributed to balance recovery by postponing the transfer of arm angular momentum to the trunk. This resulted in an axial rotation of the lower segments of the body towards the non-tripped side, which increases the length of the recovery step in the sagittal plane, and therefore facilitates braking the impending fall.

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Introduction

In order to understand balance recovery after a gait perturbation, many studies have investigated responses to slips and trips (for overviews see van Dieën et al. 2005; Grabiner et al. 2008; Lockhart 2008). A perturbation of the swing limb during gait, such as a trip over an obstacle, generally induces a forward body rotation that must be counteracted to prevent a fall. Push off by the support limb and placing the recovery foot forward as far as possible can be effective ways of braking this forward angular momentum (Grabiner et al. 1993; Pavol et al. 2001; Pijnappels et al. 2004). In both ipsilateral and contralateral leg muscles, response reactions serving these purposes have been observed at latencies of ∼65–80 ms after trip initiation (Eng et al. 1994; Schillings et al. 2000; Pijnappels et al. 2005).

Vigorous arm movements have been observed after perturbations of gait (Dietz et al. 2001; Marigold et al. 2003; Misiaszek 2003; Roos et al. 2008) and of upright stance (McIlroy and Maki 1995; Allum et al. 2002). These studies showed arm muscle response latencies of ∼80 ms. Despite detailed descriptions of arm movements and muscle activation in these studies, the function of these arm movements remains unclear. Aspecific startle responses have been suggested, but ruled out as an explanation, because there was neither habituation after repeated exposure, nor a flexor pattern as would be typical for such responses (McIlroy and Maki 1995; Misiaszek 2003). More likely, the arms may serve a protective function, to reach or grasp for external supports or to brace for impact in preparation of a possible fall (McIlroy and Maki 1995; Maki and McIlroy 1997; Allum et al. 2002; Misiaszek 2003; Kim and Robinson 2005). Alternatively, the arm movements may serve to affect the mechanics of the body, for example, as a counterweight to shift the body center of mass (COM) away from the direction of the fall (Marigold et al. 2003; Misiaszek 2003) or by generating a reactive torque to counteract the whole-body angular momentum (Allum et al. 2002; Hof 2007; Roos et al. 2008).

Roos et al. (2008) recently investigated arm movements in trip recovery. They observed asymmetric arm movements, which displaced the arm COM upward relative to the COM of the rest of the body and assumed that anteflexion of the arms served to reduce the forward body angular momentum in the sagittal plane. However, they did not quantify the actual effects on body angular momentum or rotation. Furthermore, analyses were limited to 2D, whereas contact forces during tripping may induce substantial angular motions in the frontal and transverse planes (van der Burg et al. 2005).

The aim of this study was to determine if and how arm movements play a functional role in balance recovery after a perturbation. We tripped young adults over an obstacle and measured the activation pattern of five pairs of bilateral shoulder muscles. Full body 3D kinematics were measured and used to quantify the 3D angular momentum and orientation of the body. If arm movements play a biomechanical role in restoring the normal gait kinematics following an asymmetric perturbation, specific (i.e. asymmetric) muscle responses would be expected. When resulting arm movements serve a protective function, a (symmetric) anteflexion would be expected when there is no handrail or wall to grasp (Hsiao and Robinovitch 1997), in anticipation of braking the possible fall. If arm movements contribute to balance recovery, 3D mechanical analysis would reveal a beneficial effect on the orientation of the body. Considering the asymmetric arm movements observed by Roos et al. (2008), we hypothesized that arm movements contribute to balance recovery. Our specific aim was to quantify this contribution. Furthermore, we hypothesized that specific muscle activation patterns rather than passive motions or aspecific startle responses would initiate the arm movements.

Methods

Ten healthy participants (6 males and 4 females) voluntarily participated in this study. Mean age was 25 (standard deviation (SD) 3) years, mean height 1.79 (SD 0.08) meters and mean mass of the subjects was 73 (SD 7) kg. The local ethics committee approved the procedure and all subjects gave their written, informed consent, in accordance with the ethical standards of the declaration of Helsinki, before participation.

Experimental setup and protocol

Subjects were invited to walk, at a self-selected walking velocity, over a 12 $\times$ 2.5-m platform in which 14 obstacles were hidden on the left side and 7 on the right side (see Fig. 1). After at least 10 normal walking trials, in about 10 out of 70 walking trials, subjects were tripped by one of these 15-cm-high obstacles that suddenly appeared from the floor ($\sim$100 ms prior to impact). In the first trial of each subject, an obstacle blocked the subjects' left foot. At the start of each trial, subjects did not know whether an obstacle would appear, and if so, at what side or in what phase of the gait cycle. On-line kinematic data were used to calculate when and which obstacles on the left side of the platform had to appear to initiate a trip at mid-swing (Pijnappels et al. 2005). A typical reaction to a trip during mid-swing is an elevating strategy, consisting of an elevation of the obstructed swing limb over the obstacle (Eng et al. 1994; Schillings et al. 2000). For this strategy, the tripped foot is coined the recovery foot. Subjects wore a safety harness, attached to a ceiling-mounted rail. The harness prevented a possible fall on the floor, but provided enough freedom of movement to not influence the gait pattern or tripping reaction. No objects or safety rails were available toward which subjects could reach (Fig. 1).

For the quantification of body rotation with and without the use of arms, we included an experimental condition in which subjects walked with their arms clasped on the back. It appeared, however, that this condition was not useful for comparison, since the arm swing plays a major role in the control of angular momentum in unperturbed walking (Elftman 1939; Bruijn et al. 2008; Ortega et al. 2008). As a result, the boundary conditions (i.e. trunk angle and angular momentum) at the instant of tripping were not comparable to normal walking. Moreover, subjects were unable to keep their arms on their back after tripping. We therefore quantified the contribution of arm movements by a numerical calculation as described below.

Data collection and analysis

For this study, only the first tripping trial was analyzed, to minimize a possible effect of habituation. Kinematic data were recorded by 26 infra-red markers at a sample rate of 100 Hz using 4 arrays of Optotrak cameras (Northern Digital®, Waterloo, Canada). On the legs, markers were placed bilaterally over the fifth metatarsophalangeal joint (MTP5), lateral malleolus, lateral epicondyle and the trochanter major. For the pelvis, trunk, upper arms, and lower arms, clusters of three markers were placed on a small

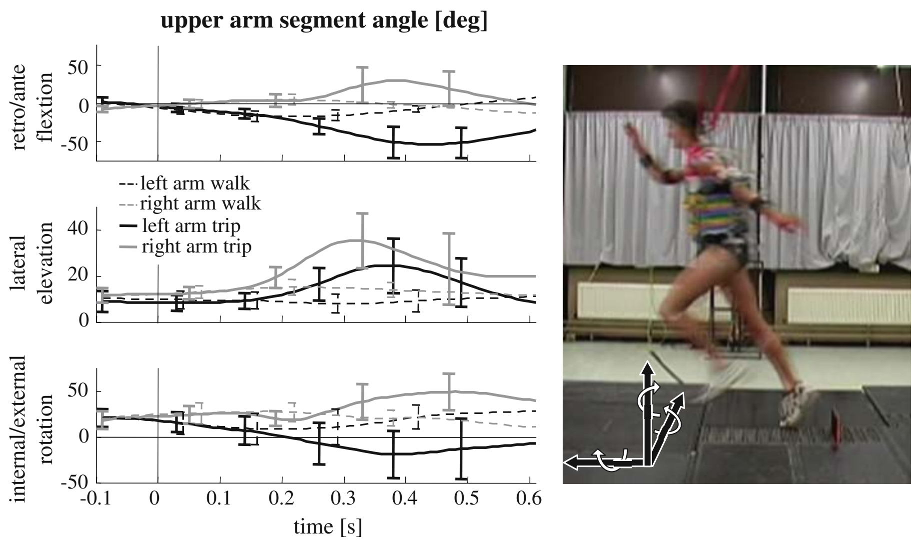

Fig. 1 *Left* Upper arm segment angles (deg), about three axes, during walking and after tripping of the left foot, averaged (and SD) over subjects. The *vertical lines* ($t = 0$ s) indicate trip initiation. The typical asymmetric arm movements after tripping were retroflexion, abduction and internal rotation of the arm on the tripped (*left*) side, and anteflexion, abduction and external rotation of the arm on the non-tripped side. *Right* Picture of a subject during tripping with the axes system, with *arrows* indicating positive (rotational) directions. Note that anteflexion of the arms segment is defined as a backward rotation

metal plate strapped to each body segment. Cluster markers were related to anatomical landmarks by making a short recording while pointing at each landmark (Cappozzo et al. 1995) with a pointer containing six markers, thus allowing reconstruction of the local anatomical axes on each segment at each instant of time. Ground reaction forces under the right, non-tripped, foot were recorded by a custom-made strain gauge force plate (1 × 1 m). Movements, forces and center of pressure (COP) were smoothed with a second order low-pass Butterworth filter with a cutoff frequency of 6 Hz. The head was assumed to be rigidly connected to the trunk. Heel strike, toe-off and obstacle-foot contact were determined based on kinematic data (Pijnappels et al. 2001).

Muscle activity patterns were recorded at the skin overlying the left and right main shoulder muscles: m. pectoralis major, m. deltoideus pars clavicularis, m. deltoideus pars acromialis, m. biceps brachii, and m. triceps brachii. Bipolar Ag/AgCl surface electrodes (Medicotest®) were placed over the muscle belly in line with the muscle fibers. The electromyogram (EMG) signals were amplified by a factor of 20 (Porti-17™, Twente Medical Systems), high-pass filtered (5 Hz), and stored on disk at a sample rate of 1,000 samples s^{-1} with a 22-bit resolution. Next, the signals were whitened (fifth order) to reduce the influence of tissue filtering and movement artefacts, Hilbert transformed, rectified and finally low-pass filtered with a fifth order (frame size 21) Savitzky–Golay filter (see Pijnappels et al. 2005). For onset detection of increases in muscle activity, we subtracted the averaged time series pattern of two normal walking trials of each subject from the time series of the tripping trial (in mV), aligned on heel strike. Onset was determined on these subtracted signals according to the method described by Staude and Wolf (1999). This method searches for changes in the EMG sequence after trip initiation by use of the likelihood ratios over small time windows. Furthermore, we calculated for each subject and muscle the mean amplitudes of the subtracted signals over 200 ms after trip initiation.

A 12-segment 3D model, based on kinematic and gender-specific anthropometric data (according to McConville et al. 1980; Young et al. 1983), was used to calculate the angular momentum of all segments about the center of mass (COM) of the summed segments. The 3D angular momentum of the body, or a subset of body segments, was calculated using the following equation:

$$\mathbf{L}_{\mathrm{sum}} = \sum \left(\mathbf{I}_j \cdot \boldsymbol{\omega}_j + (m_j \cdot \mathbf{r}_j \times \dot{\mathbf{r}}_j) \right) \quad (1)$$

where $\mathbf{I}_j$ is the instantaneous inertia tensor of the jth segment relative to its COM, $\boldsymbol{\omega}_j$ is the angular velocity vector of the segment, m_j is the segment mass, $\mathbf{r}_j$ is the position vector from the COM of the summed segments to the segment COM and $\dot{\mathbf{r}}_j$ is the velocity vector of the segment COM relative to the COM of the summed segments. Using Eq. 1, we also calculated the angular momentum of the arms ($\mathbf{L}_{\mathrm{arms}}$) and of all segments except the arms ($\mathbf{L}_{\mathrm{trunklegs}}$).

To quantify the contribution of arm movements to balance recovery, we compared the actual angular displacement of the trunk + legs after trip initiation until recovery foot landing to the angular displacement of the trunk + legs that would have occurred if the arms were removed at the instant of tripping.

In normal gait, the arm swing causes substantial angular momentum in the arms, the direction of which is reversed at each step by exchange of angular momentum with the rest of the body (Bruijn et al. 2008). At mid-swing, i.e., at the instant our subjects were tripped, the angular momentum of the arms reaches a maximum, in which the right arm moves forward at maximum velocity and the left arm moves backward at maximum velocity. Therefore, we anticipated that the effect of arm removal would be different if the angular momentum of the arms at the instant of tripping is assigned to either the arms or to the rest of the body. Therefore, we calculated the effect of arm removal both with and without transfer of the angular momentum of the arms at the instant of tripping. Specifically, we defined a 'cut' condition in which the arms kept their own angular momentum after cutting so that it was not transferred to the rest of the body at all. A 'transfer&cut' was defined in which the angular momentum of the arms was transferred to the rest of the body at the instant of tripping.

The equations of motions used to calculate the angular momentum of the 'armless body', further denoted as 'trunk + legs', are:

$$\mathbf{L}_{\text{trunklegs\_armless}} = \mathbf{L}_{\text{arms}} - \mathbf{L}_{\text{arms,trip}} + \mathbf{L}_{\text{trunklegs}} + \int_{t=\text{trip}}^{t=\text{lift-off}} ((\mathbf{r}_{\text{arms}} - \mathbf{r}_{\text{COP}}) \times m_{\text{arms}} \cdot (\mathbf{a}_{\text{arms}} - \mathbf{g}))\mathrm{d}t \quad (2)$$

for the 'cut' condition and

$$\mathbf{L}_{\text{trunklegs\_armless}} = \mathbf{L}_{\text{arms}} + \mathbf{L}_{\text{trunklegs}} + \int_{t=\text{trip}}^{t=\text{lift-off}} ((\mathbf{r}_{\text{arms}} - \mathbf{r}_{\text{COP}}) \times m_{\text{arms}} \cdot (\mathbf{a}_{\text{arms}} - \mathbf{g}))\mathrm{d}t \quad (3)$$

for the 'transfer&cut' condition. In these equations, $\mathbf{r}$ = position vector, m = mass, $\mathbf{a}$ = acceleration vector, $\mathbf{g}$ = gravity vector, and x = vector product. For derivation of these equations, see the Appendix.

From these angular momenta, the angular displacement of the trunk + legs between trip initiation and recovery foot landing was abstracted. This was to be applied for three conditions, i.e., for the actual $\mathbf{L}_{\text{trunklegs}}$ as well as for $\mathbf{L}_{\text{trunklegs\_armless}}$ in both the 'transfer& cut' and the 'cut' conditions. Together, these three conditions are indicated as *, e.g. in $\mathbf{L}_{\text{trunklegs\_*}}$. For each condition, the angular velocity vector of the combined trunk + legs segment, $\boldsymbol{\omega}_{\text{trunklegs\_*}}$, was calculated at each instant of time between trip and recovery foot landing from:

$$\mathbf{L}_{\text{trunklegs\_*}} = \mathbf{I}_{\text{trunklegs}} \cdot \boldsymbol{\omega}_{\text{trunklegs\_*}} \quad (4)$$

where $\mathbf{I}_{\text{trunklegs}}$ is the instantaneous actual inertia tensor of the trunk + legs. This tensor can be calculated from the inertia tensors of the individual body segments using the parallel axes theorem. Finally, we obtained the total (virtual) rotation of the trunk + legs segment between trip and recovery foot landing by using numerical integration, or more precisely, by a progressive sample-by-sample application of $\boldsymbol{\omega}_{\text{trunklegs\_*}}$ to an orientation matrix aligned with the global system of axes at trip initiation. Subsequently, the resulting matrix was decomposed in the order sagittal plane–frontal plane–transverse plane to obtain the angular change of the trunk + legs ($d\phi_{\text{trunklegs\_*}}$) between trip initiation and recovery foot landing.

For statistical analysis of differences in EMG responses between the tripped and non-tripped sides, the onsets and mean amplitudes of left and right arm muscles were tested for each muscle by univariate one-way analysis of variance (ANOVA's) for repeated measures. The differences in relative orientation of the trunk + legs between the actual tripping condition and the analytical calculations 'transfer&cut' and 'cut' were statistically analyzed for each plane by ANOVA's for repeated measures, with post hoc paired t tests. All statistical analyses were performed using SPSS (version 16.0). The level of significance was set at 0.05.

Results

Subjects walked at an average velocity of 1.54 (SD 0.14) m s^{-1}. When tripped, all subjects showed the elevating strategy and were able to recover their balance without falling. The recovery phase, i.e., the time between trip initiation and recovery foot landing, was 514 (SD 24) ms, which included an averaged aerial phase between liftoff of the non-tripped foot and landing of the recovery foot of 77 (SD 69) ms. After tripping, typical asymmetric arm movements were observed in all subjects: retroflexion of the arm on the tripped side (left) and anteflexion of the arm on the non-tripped side (Fig. 1). Note that the arms already moved in those directions, but the amplitudes of the normal movements were amplified. Furthermore, abduction was observed in both arms. These asymmetric arm movements indicate that they did not serve a protective function in anticipation of braking the possible fall.

Muscle activity

Strong asymmetric shoulder muscle responses were observed within 100 ms after trip initiation (Fig. 2). A

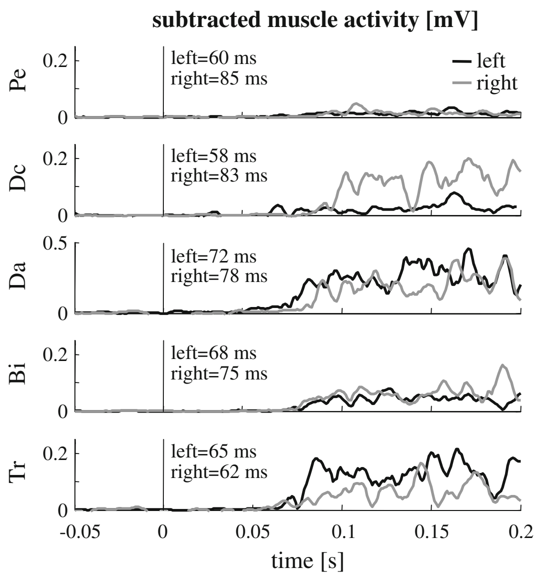

Fig. 2 Typical muscle activity pattern (mV) and onset times, with the pattern during normal gait subtracted, of one subject after tripping for the left (ipsilateral) and right (contralateral) shoulder muscles: m. pectoralis major (*Pe*), m. deltoideus pars clavicularis (*Dc*), m. deltoideus pars acromialis (*Da*), m. biceps brachii (*Bi*), and m. triceps brachii (*Tr*). The *vertical lines* ($t = 0$ s) indicate trip initiation

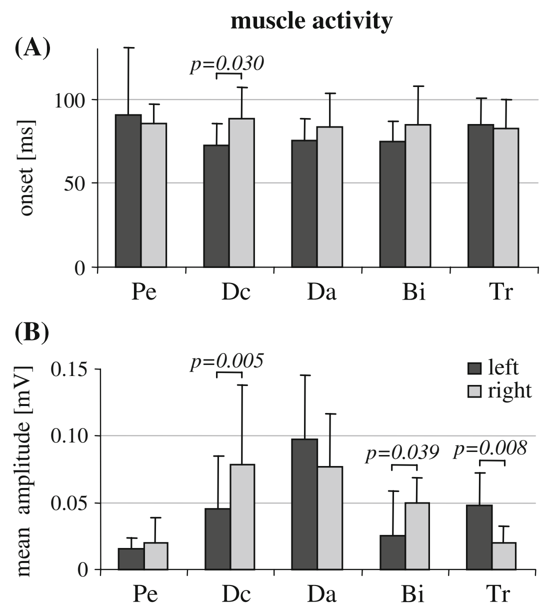

Fig. 3 **a** Onset times and **b** mean amplitudes over 200 ms after trip initiation (all averaged and SD over subjects) of EMG signals with normal gait subtracted, for left and right shoulder muscles: m. pectoralis major (*Pe*), m. deltoideus pars clavicularis (*Dc*), m. deltoideus pars acromialis (*Da*), m. biceps brachii (*Bi*), and m. triceps brachii (*Tr*). Significant differences between sides are indicated with *p* values

significantly faster response was found in the m. deltoideus pars clavicularis on the tripped (left) side compared to the non-tripped side (Fig. 3a). Furthermore, amplitudes of muscle activity averaged over 200 ms after trip initiation were larger in the retroflexors (m. triceps brachii) on the tripped side and in the anteflexors (m. deltoideus pars clavicularis and m. biceps brachii) on the non-tripped side (Fig. 3b). These specific, active responses indicate that the arm movements did not result from passive mechanics nor from aspecific startle responses.

Angular momentum and trunk + legs rotation

In the sagittal plane, impact with the obstacle induced an angular momentum that tended to rotate the body forward after trip initiation (Fig. 4). During the recovery phase, the resultant angular momentum of the two arms was slightly forward (Fig. 4). This implies that the forward arm rotation (note that this is shoulder retroflexion) on the tripped side was faster than the backward arm rotation on the non-tripped side (Fig. 1). However, when we compared the 'transfer&cut' and 'cut' calculations with actual tripping, only minor differences in angular velocity of the trunk + legs were observed (Fig. 5). The resultant rotation of trunk + legs between trip and recovery foot landing in the sagittal plane showed no significant differences between conditions ($p = 0.108$) (Fig. 6).

In the frontal plane, impact with the obstacle tended to rotate the body towards the tripped side (Fig. 4). During the recovery phase, both arms were laterally elevated (Fig. 1). The lateral elevation of the right arm preceded the lateral elevation of the left arm, so that the resultant angular momentum of the two arms was first slightly towards the tripped side and then towards the non-tripped side (Fig. 4). The effect of the arms on the resulting trunk + legs rotation between trip and recovery foot landing, was significant ($p = 0.004$) but small (Fig. 6). The 'transfer&cut' condition predicted 8.5° (SD 4.1) rotation to the tripped side, and this was 2.9° (SD 3.4) more than in the actual trip condition ($p = 0.025$). For the 'cut' condition, the difference with the actual trip was not significant. These results suggest that transfer of the initial arm angular momentum is unfavorable for balance recovery as it increases the rotation towards the tripped side, which hampers taking a large recovery step. The arm movements in the frontal plane contribute to postpone this transfer.

In the transverse plane, the effect of arm motions was significant, shown by a main effect of condition on rotation of the trunk + legs between trip initiation and recovery foot landing ($p < 0.001$). The effect of the arms was much larger in this plane than in the other two planes. This is due to the fact that, in normal gait as well as in response to tripping, the sign of the angular momentum of the two arms is opposite in the sagittal and frontal planes, but the same in the transverse plane. Impact with the obstacle tended to rotate the total body towards the tripped side (Fig. 4). Note

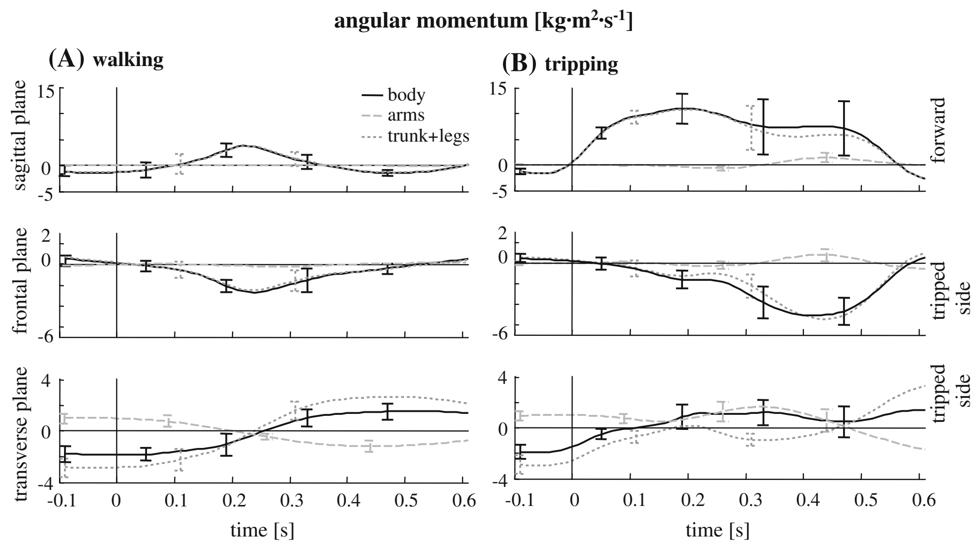

Fig. 4 Angular momentum [kg m^2 s^{-1}] averaged (and SD) over subjects, in three planes for the total body, arms, and trunk + legs, **a** during normal walking and **b** in the actual tripping condition. A positive angular momentum indicates a forward angular velocity in the sagittal plane, an angular velocity towards the non-tripped side in the frontal plane and an angular velocity towards the tripped side in the transverse plane. The vertical lines ($t = 0$ s) indicate trip initiation (or intended trip initiation for walking)

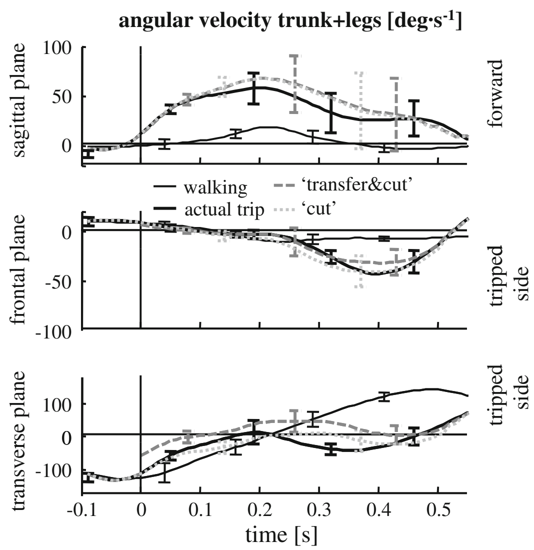

Fig. 5 Angular velocity (deg s^{-1}) averaged (and SD) over subjects, in three planes of the trunk + legs, during normal walking, for the actual tripping condition and for the 'transfer&cut' and 'cut' calculations. The *vertical lines* ($t = 0$ s) indicate trip initiation

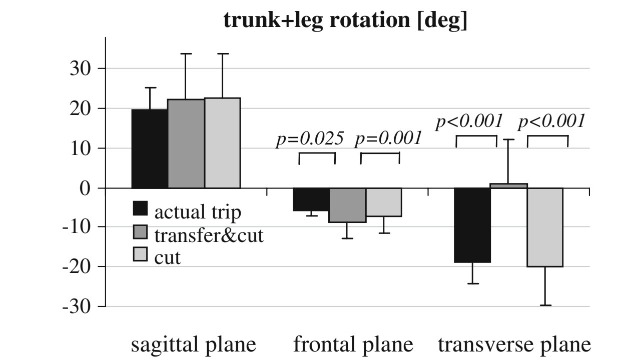

Fig. 6 Rotation of the trunk + legs from trip initiation until landing of the recovery foot, in three planes averaged (and SD) over subjects, for the actual tripping condition and for the 'transfer&cut' and 'cut' calculations. Positive directions are forward rotation in the sagittal plane; towards the non-tripped side in the frontal plane, and towards the tripped side in the transverse plane. Statistically significant differences between conditions are indicated with p values

that the resultant arm angular momentum towards the tripped side was opposite to that of trunk + legs at trip initiation and shortly after tripping. The angular momentum of the summed arms in the transverse plane (Fig. 4) shows that, whereas in normal gait its sign reverses about 250 ms after mid-swing, arm swing is prolonged and first even accelerated after tripping. On average, the angular momentum of the summed arms in the transverse plane between trip initiation and recovery foot landing remained at about the level it had at trip initiation (Fig. 4). Consequently, the angular velocity of trunk + legs was very similar between the actual trip and the 'cut' condition (Fig. 5), which simulates that the arms would completely keep their angular momentum after trip initiation. The resultant trunk + legs rotation at recovery foot landing was not significantly different between the 'cut' condition and the actual trip (Fig. 6).

Because the angular momentum of the summed arms was positive (i.e., towards the tripped side) and quite substantial at trip initiation (Fig. 4), the 'transfer&cut' calculation predicted a sudden increase of the angular velocity of the trunk + legs (Fig. 5). As a result, the trunk + legs would rotate 0.8° to the tripped side in the 'transfer&cut' calculation instead of 18.9° (SD 5.3) to the non-tripped side for the actual trip (Fig. 6).

Discussion

Arm movements after perturbations like tripping over an obstacle have been suggested to either serve a protective function or affect the mechanics of the body. This study was aimed at determining if and how arm movements play a functional role in balance recovery after tripping.

Arm muscle activity

If arm movements play a functional role in trip recovery, we expected specific muscle responses. Indeed, our results showed specific, asymmetric muscle activity in the shoulder muscles after the perturbation, with latencies similar to responses in leg muscles (Eng et al. 1994; Schillings et al. 2000; Pijnappels et al. 2005). This underlines that arm movements were not aspecific startle responses. Although one study found habituation of arm muscle activation following consecutive slips (Marigold et al. 2003), other studies on perturbations during upright stance and walking showed that there was no habituation in arm movements (McIlroy and Maki 1995; Misiaszek 2003), which is in line with our findings indicating that those movements are not startle responses. The asymmetry of the resulting arm movements in this study further indicated that these movements did not serve a protective function in anticipation of braking the possible fall, as that would require a symmetric forward arm elevation (Allum et al. 2002). It seems therefore that arm movements after tripping are neither aspecific nor aimed at refracting a possible fall, but instead play a functional role in balance recovery.

Arm movements

After concluding that arm movements have a functional role, the next question to answer is how the arms contribute to balance recovery. Previous studies suggested that the arms might affect the mechanics of the body (Allum et al. 2002; Marigold et al. 2003; Misiaszek 2003; Roos et al. 2008). Yet, none of these studies have actually quantified the 3D mechanical contribution of arm movements.

We showed that the asymmetric arm movements affected rotation in the transverse plane more prominently than in the sagittal and frontal planes. In contrast to our findings, Roos et al. (2008) reported, based on a 2D study, a substantial effect of arm movement in the sagittal plane on balance recovery after a trip. They found that, in young subjects, the angular momentum of the arms due to forward elevation between trip initiation and landing of the recovery foot was about 13% of the angular momentum of the whole body. Based on this result, they concluded that forward elevation of the arms served to reduce the forward body angular momentum in the sagittal plane. However, the contribution of the arms to balance recovery cannot directly be abstracted from such a percentage. First, it ignores the law of impulse preservation which is operative during the aerial phase. Second, adequate balance recovery not only depends on the whole-body angular momentum, but also on the final body orientation. Irrespective of changes in the whole-body angular momentum, arm elevation increases the moment of inertia of the body, which slows down the angular velocity of the whole body. Understanding the contribution of the arms to balance recovery requires therefore consideration of not only the angular momentum, but also of the resulting angular velocity and angular orientation.

Contribution of arm angular momentum on body orientation

Our 3D method takes these considerations of momentum and inertial effects of arm movements on the final body orientation as well as changes in trunk + legs angular momentum into account.

In normal gait, arm angular momentum is constantly exchanged with the rest of the body and is largest at midswing, i.e. at the instant the subjects were tripped. At this instant, the arms move in opposite direction in the sagittal and frontal planes, whereas in the transverse plane, both arms contribute to an angular momentum in the same direction, opposite to that of the trunk + legs. After tripping, prolongation of the ongoing retroflexion of the arm on the tripped (left) side and anteflexion of the arm on the non-tripped side, combined with abduction in both arms were observed.

In none of the three planes, the ‘cut’ calculation resulted in a trunk + legs rotation that differed significantly from the actual trip, whereas the ‘transfer&cut’ calculation resulted in a significantly less favorable trunk + legs rotation in the frontal and transverse planes. As the ‘cut’ condition simulates a full conservation of the arm angular momentum in the arms themselves after the trip, in contrast to the ‘transfer&cut’ condition which simulates a direct transfer of the arm angular momentum to the trunk + legs, these findings suggests that arm motions after tripping can mainly be seen as an attempt to prolong the arm swing, in other words, to delay return of arm angular momentum to the rest of the body during the recovery step. Largest and most significant effects of arm movements on balance recovery were found in the transverse plane. During normal walking, the arms have substantial angular momenta around the vertical axis through the body center (Elftman 1939; Bruijn et al. 2008). The angular momentum of the summed arms is largest at trip initiation at mid-swing. By prolongation of the arm swing in case of a trip, the angular momentum of the arms remained towards the tripped side after trip initiation, which implies that less angular momentum is transferred to the trunk + legs compared to normal walking. Hence, trunk + legs could rotate further towards the non-tripped side. Importantly, the resulting axial rotation of the trunk + legs towards the non-tripped

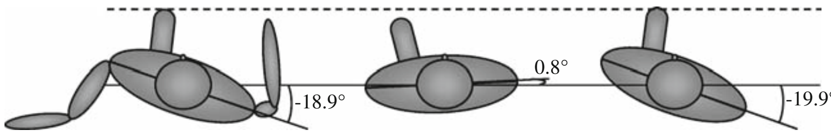

Fig. 7 Top view of the orientation of the trunk + legs at recovery foot landing for the actual tripping condition and for the 'transfer&cut' and 'cut' calculations. Positive direction in this transverse plane is towards the tripped (left) side. Note that the numerical calculations are the virtual representations of the trunk + legs orientation if the arms would not contribute to balance recovery and if the behavior of the trunk and leg muscles would be unaltered

side in the transverse plane enhances the length of the recovery step in the sagittal plane (Fig. 7), which needs to be as large as possible, which facilitates recovery (Grabiner et al. 1993; Pavol et al. 2001; Hof et al. 2005). So the arm movements contributed to a more adequate body orientation after a trip, mainly by postponing the unfavorable effect of transferring the initial arm momentum in the transverse plane to the trunk in order to facilitate a more favorable orientation of the trunk + legs for recovery foot landing.

Limitations

Our model was based on assumptions regarding the inertial properties of the body segments, the location and degrees of freedom of the joints, the effects of soft-tissue movement on the LED locations, and the accuracy and resolution of the motion capture system. The model has previously been validated with respect to these aspects (Kingma et al. 1996) and the effects thereof can be assumed to be relatively small and will not affect the outcomes of our study.

In our calculations, we assumed the COP to be under the right foot as measured by the force plate. This might have introduced a small error for $\mathbf{r}_{COP}$ in Eqs. 2 and 3 during contact of the tripped foot with the obstacle as these contact forces could not be quantified. Based on an estimation of the size and duration of the contact force with the obstacle (Grabiner et al. 1993; Pavol et al. 2001; Pijnappels et al. 2004), we calculated the size of this effect on the trunk + legs rotation. This resulted in trunk + legs rotations smaller than 1° (SD < 0.38) for all calculations, which would not have affected our results or conclusions.

We did not investigate effects of arm motions on COM trajectory. As we noticed that the arms moved in opposite direction after tripping in both the frontal and sagittal planes, the effects of arm motions on COM can only have been small, and are thus not likely to contribute much to recovery. Moreover, the nature of the tripping perturbation is mainly rotational, so that an analysis of rotational motion is the most direct way to disentangle the consequences of the trip and recovery response.

It should further be noted that the predicted orientations in our virtual 'cut' and 'transfer&cut' calculations were based on the assumption that no changes in behavior of the lower segments would occur. It can be expected that in an actual trip without arm use or with less adequate arm movements, the legs will contribute more to reduction of the body angular momentum by higher lower limb forces (Misiaszek and Krauss 2005). This indeed seemed the case in our experimental attempt to trip subjects while walking with their arms clasped on the back, in which balance recovery was possible. However, as described before, this condition could not be used to quantify the effect of the arm movements. Furthermore, our subjects were healthy young adults who all were able to regain balance after tripping and none of them fell into the harness when tripped.

Finally, subjects were tripped at one specific instant of the gait cycle. The angular momentum of the arms at that instant highly affects the resultant arm motion after tripping. Therefore, it can be expected that, for tripping at other instants of the gait cycle and for other perturbations such as slipping, the arm motions or their functionality may differ.

Conclusion

In conclusion, specific, asymmetric muscle activity in the shoulder muscles after tripping contribute to balance recovery by counteracting the body rotation in the transverse plane in order to achieve a favorable body orientation for adequate recovery foot positioning. Postponing a transfer of the initial angular arm momentum at trip initiation is the most important factor of the contribution of arm movements to successful recovery from a trip.

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Appendix

Equations of motion for armless body

First, the body was separated in two segment sets, arms (two arms) and trunk + legs (trunk plus two legs). For

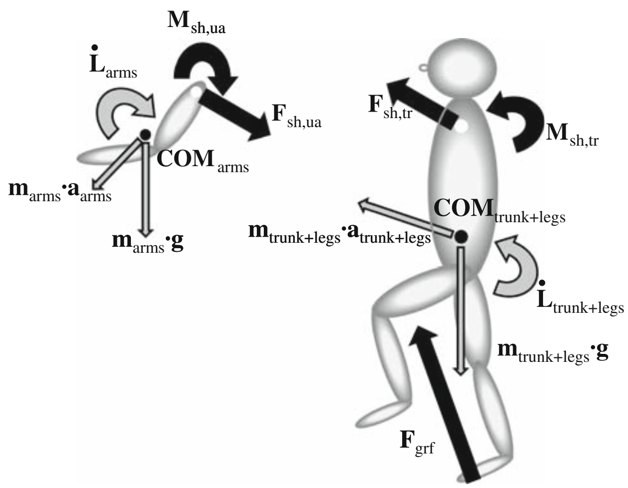

Fig. 8 Free body diagram of the two segment sets arms and trunk + legs. Note that the arms segments set represents both arms. Forces and moments are represented in *black arrows*; linear and angular acceleration terms in *grey arrows*. Abbreviations are explained in the text of the Appendix

these two segment sets, the equations of motion, with moment equations around the center of mass, are (see Fig. 8):

$$\mathbf{F}_{sh,ua} = m_{arms} \cdot (\mathbf{a}_{arms} - \mathbf{g}) \tag{5}$$

$$\dot{\mathbf{L}}_{arms} = \mathrm{d}(I\omega)\mathrm{d}t = \mathbf{M}_{sh,ua} + (\mathbf{r}_{sh} - \mathbf{r}_{arms}) \times \mathbf{F}_{sh,ua} \tag{6}$$

$$\mathbf{F}_{grf} = m_{trunklegs} \cdot \left(\mathbf{a}_{trunklegs} - \mathbf{g}\right) - \mathbf{F}_{sh,tr} \tag{7}$$

$$\begin{aligned}\dot{\mathbf{L}}_{trunklegs} = \mathbf{M}_{sh,tr} &+ \left(\mathbf{r}_{sh} - \mathbf{r}_{trunklegs}\right) \times \mathbf{F}_{sh,tr} \\ &+ \left(\mathbf{r}_{COP} - \mathbf{r}_{trunklegs}\right) \times \mathbf{F}_{grf} + \mathbf{M}_{grf}\end{aligned} \tag{8}$$

where $\mathbf{g}$ = gravity vector, m = mass, $\mathbf{a}$ = acceleration vector, $\mathbf{r}$ = position vector, $\dot{\mathbf{L}}$ = rate of change of the angular momentum, $\mathbf{x}$ = vector product, $\mathbf{F}_{sh}$ and $\mathbf{M}_{sh}$ = reaction force and moment at the shoulder, with $_{tr}$ = on the trunk and $_{ua}$ = on the upper arm. Furthermore, $\mathbf{F}_{grf}$ = ground reaction force, $\mathbf{M}_{grf}$ = ground reaction moment (only non-zero around the vertical axis) and COP = center of pressure. Inserting Eq. 7 into 8 yields:

$$\begin{aligned}\dot{\mathbf{L}}_{trunklegs} = \mathbf{M}_{sh,tr} &+ \left(\mathbf{r}_{sh} - \mathbf{r}_{trunklegs}\right) \times \mathbf{F}_{sh,tr} \\ &+ \left(\mathbf{r}_{COP} - \mathbf{r}_{trunklegs}\right) \times m_{trunklegs} \cdot \left(\mathbf{a}_{trunklegs} - \mathbf{g}\right) \\ &- \left(\mathbf{r}_{COP} - \mathbf{r}_{trunklegs}\right) \times \mathbf{F}_{sh,tr} + \mathbf{M}_{grf}\end{aligned} \tag{9}$$

From the instant of trip initiation onward, we simulated arm removal so that $\mathbf{F}_{sh,tr}$ and $\mathbf{M}_{sh,tr}$ are zero and Eq. 9 simplifies to:

$$\begin{aligned}\dot{\mathbf{L}}_{trunklegs\_armless} = \left(\mathbf{r}_{COP} - \mathbf{r}_{trunklegs}\right) \times m_{trunklegs} \\ \cdot \left(\mathbf{a}_{trunklegs} - \mathbf{g}\right) + \mathbf{M}_{grf}\end{aligned} \tag{10}$$

Theoretically, this equation can be used to achieve our objective, i.e., to calculate the angular displacement of the trunk + legs without arms between trip initiation and recovery foot landing. However, to calculate angular displacement, this equation would require double numerical integration, which strongly amplifies errors, such as the error in $\mathbf{r}_{COP}$ during contact of the tripped foot with the obstacle. We therefore introduced an alternative solution. As $\mathbf{M}_{sh,tr} = -\mathbf{M}_{sh,ua}$, and $\mathbf{F}_{sh,tr} = -\mathbf{F}_{sh,ua}$, Eq. 6 can be used to rewrite Eq. 9 to:

$$\begin{aligned}\dot{\mathbf{L}}_{trunklegs} = &- \left(\dot{\mathbf{L}}_{arms} - \left(\mathbf{r}_{sh} - \mathbf{r}_{arms}\right) \times \left(-\mathbf{F}_{sh,tr}\right)\right) \\ &+ \left(\mathbf{r}_{sh} - \mathbf{r}_{trunklegs}\right) \times \mathbf{F}_{sh,tr} \\ &+ \left(\mathbf{r}_{COP} - \mathbf{r}_{trunklegs}\right) \times m_{trunklegs} \cdot \left(\mathbf{a}_{trunklegs} - \mathbf{g}\right) \\ &- \left(\mathbf{r}_{COP} - \mathbf{r}_{trunklegs}\right) \times \mathbf{F}_{sh,tr} + \mathbf{M}_{grf}\end{aligned} \tag{11}$$

which can be simplified to:

$$\begin{aligned}\dot{\mathbf{L}}_{trunklegs} = &- \dot{\mathbf{L}}_{arms} + \left(\mathbf{r}_{arms} - \mathbf{r}_{COP}\right) \times \mathbf{F}_{sh,tr} \\ &+ \left(\mathbf{r}_{COP} - \mathbf{r}_{trunklegs}\right) \times m_{trunklegs} \\ &\cdot \left(\mathbf{a}_{trunklegs} - \mathbf{g}\right) + \mathbf{M}_{grf}\end{aligned} \tag{12}$$

Now Eq. 10 can be used to replace the right terms in Eq. 12 by $\dot{\mathbf{L}}_{trunklegs\_armless}$:

$$\begin{aligned}\dot{\mathbf{L}}_{trunklegs} = &-\dot{\mathbf{L}}_{arms} + \left(\mathbf{r}_{arms} - \mathbf{r}_{cop}\right) \times \mathbf{F}_{sh,tr} \\ &+ \dot{\mathbf{L}}_{trunklegs\_armless}\end{aligned} \tag{13}$$

which can be rearranged using Eq. 5 and $\mathbf{F}_{sh,tr} = -\mathbf{F}_{sh,ua}$:

$$\begin{aligned}\dot{\mathbf{L}}_{trunklegs\_armless} = \dot{\mathbf{L}}_{arms} + \dot{\mathbf{L}}_{trunklegs} + (\mathbf{r}_{arms} - \mathbf{r}_{COP}) \\ \times m_{arms} \cdot (\mathbf{a}_{arms} - \mathbf{g})\end{aligned} \tag{14}$$

Now the angular momentum $\mathbf{L}_{trunklegs\_armless}$ at the time range from trip to recovery foot landing can be calculated by integrating Eq. 14:

$$\begin{aligned}\mathbf{L}_{trunklegs\_armless} &= \mathbf{L}_{arms} + \mathbf{L}_{trunklegs} \\ &+ \int_{t=trip}^{t=lift-off} \left((\mathbf{r}_{arms} - \mathbf{r}_{COP}) \times m_{arms} \cdot (\mathbf{a}_{arms} - \mathbf{g})\right)\mathrm{d}t\end{aligned} \tag{15}$$

Note that the integral term on the right is only non-zero between trip initiation and liftoff of the non-tripped leg. This is not the case for and $\mathbf{L}_{arms}$ and $\mathbf{L}_{trunklegs}$, which are non-zero at the initiation of the trip so that:

$$\begin{aligned}\mathbf{L}_{arms} &= \mathbf{L}_{arms,trip} + \int_{t=trip}^{t=lift-off} (\mathbf{L}_{arms})\mathrm{d}t \\ \mathbf{L}_{trunklegs} &= \mathbf{L}_{trunklegs,trip} + \int_{t=trip}^{t=lift-off} \left(\mathbf{L}_{trunklegs}\right)\mathrm{d}t\end{aligned} \tag{16}$$

Importantly, $\mathbf{L}_{arms}$ and $\mathbf{L}_{trunklegs}$ can be calculated directly from the kinematics using Eq. 1 rather than by using Eq. 16. Therefore, only the rightmost term in Eq. 15 requires integration, so that application of Eq. 15 is more robust than application of Eq. 10, in that the effect of the

$\mathbf{r}_{COP}$ error during contact with the obstacle, as outlined before, is smaller than in Eq. 10.

As can be seen from Eq. 16, Eq. 15 takes into account the angular momentum of the arms and trunk + legs at the instant of trip as well. Effectively, application of Eq. 15 therefore means that, at the instant of tripping, $\mathbf{L}_{arms}$ is transferred to the trunk + legs, prior to 'cutting away' the arms. We will further denote this as the 'transfer&cut' condition. This transfer of $\mathbf{L}_{arms}$ can have substantial effects. In normal gait, the arm swing causes substantial angular momentum in the arms, the direction of which is reversed at each step by exchange of angular momentum with the rest of the body (Bruijn et al. 2008). At mid-swing, i.e., at the instant our subjects were tripped, the angular momentum of the arms reaches a maximum.

To establish the effect of the transfer of the angular momentum of the arms in the 'transfer&cut' condition, we performed an alternative calculation. In this condition, we ignored the angular momentum of the arms at the instant of tripping:

$$\mathbf{L}_{trunklegs\_armless} = \mathbf{L}_{arms} - \mathbf{L}_{arms,trip} + \mathbf{L}_{trunklegs} + \int_{t=trip}^{t=lift-off} ((\mathbf{r}_{arms} - \mathbf{r}_{COP}) \times m_{arms} \cdot (\mathbf{a}_{arms} - \mathbf{g}))dt \quad (17)$$

This calculation, to be further denoted as 'cut' condition, effectively simulates that the arms would be cut off at the instant of tripping, but would keep on rotating, i.e., would keep their own angular momentum rather than transferring it to the trunk + legs segment.

References

Allum JH, Carpenter MG, Honegger F, Adkin AL, Bloem BR (2002) Age-dependent variations in the directional sensitivity of balance corrections and compensatory arm movements in man. J Physiol 542:643–663

Bruijn SM, Meijer OG, van Diëen JH, Kingma I, Lamoth CJC (2008) Coordination of leg swing, thorax rotations, and pelvis rotations during gait: The organisation of total body angular momentum. Gait Posture 27:455–462

Cappozzo A, Catani F, Della Croce U, Leardini A (1995) Position and orientation in space of bones during movement: anatomical frame definition and determination. Clin Biomech 10:171

Dietz V, Fouad K, Bastiaanse CM (2001) Neuronal coordination of arm and leg movements during human locomotion. Eur J Neurosci 14:1906–1914

Elftman H (1939) The function of the arms in walking. Hum Biol 11:529–535

Eng JJ, Winter DA, Patla AE (1994) Strategies for recovery from a trip in early and late swing during human walking. Exp Brain Res 102:339–349

Grabiner MD, Koh TJ, Lundin TM, Jahnigen DW (1993) Kinematics of recovery from a stumble. J Gerontol A Biol Sci Med Sci 48:M97–M102

Grabiner MD, Donovan S, Bareither ML, Marone JR, Hamstra-Wright K, Gatts S, Troy KL (2008) Trunk kinematics and fall risk of older adults: translating biomechanical results to the clinic. J Electromyogr Kinesiol 18:197–204

Hof AL (2007) The equations of motion for a standing human reveal three mechanisms for balance. J Biomech 40:451–457

Hof AL, Gazendam MG, Sinke WE (2005) The condition for dynamic stability. J Biomech 38:1–8

Hsiao ET, Robinovitch SN (1997) Common protective movements govern unexpected falls from standing height. J Biomech 31:1–9

Kim BJ, Robinson CJ (2005) Postural control and detection of slip/fall initiation in the elderly population. Ergonomics 48:1065–1085

Kingma I, Toussaint HM, De Looze MP, van Dieën JH (1996) Segment inertial parameter evaluation in two anthropometric models by application of a dynamic linked segment model. J Biomech 29:693–704

Lockhart TE (2008) An integrated approach towards identifying age-related mechanisms of slip initiated falls. J Electromyogr Kinesiol 18:204–217

Maki BE, McIlroy WE (1997) The role of limb movements in maintaining upright stance: the "change-in-support" strategy. Phys Ther 77:488–507

Marigold DS, Bethune AJ, Patla AE (2003) Role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip during locomotion. J Neurophysiol 89:1727–1737

McConville JT, Churchill TD, Kaleps I, Clauser CE, Cuzzi J (1980) Anthropometric relationships of body and body segment moments of inertia. Technical Report. Aerospace Medical Research Laboratory, Ohio

McIlroy WE, Maki BE (1995) Early activation of arm muscles follows external perturbation of upright stance. Neurosci Lett 184:177–180

Misiaszek JE (2003) Early activation of arm and leg muscles following pulls to the waist during walking. Exp Brain Res 151:318–329

Misiaszek JE, Krauss EM (2005) Restricting arm use enhances compensatory reactions of leg muscles during walking. Exp Brain Res 161:474–485

Ortega JD, Fehlman LA, Farley CT (2008) Effects of aging and arm swing on the metabolic cost of stability in human walking. J Biomech 41:3303–3308

Pavol MJ, Owings TM, Foley KT, Grabiner MD (2001) Mechanisms leading to a fall from an induced trip in healthy older adults. J Gerontol A Biol Sci Med Sci 56:M428–M437

Pijnappels M, Bobbert MF, van Dieën JH (2001) Changes in walking pattern caused by the possibility of a tripping reaction. Gait Posture 14:11–18

Pijnappels M, Bobbert MF, van Dieën JH (2004) Contribution of the support limb in control of angular momentum after tripping. J Biomech 37:1811–1818

Pijnappels M, Bobbert MF, van Dieën JH (2005) How early reactions in the support limb contribute to balance recovery after tripping. J Biomech 38:627–634

Roos PE, McGuigan MP, Kerwin DG, Trewartha G (2008) The role of arm movement in early trip recovery in younger and older adults. Gait Posture 27:352–356

Schillings AM, Van Wezel BMH, Mulder T, Duysens J (2000) Muscular responses and movement strategies during stumbling over obstacles. J Neurophysiol 83:2093–2102

Staude G, Wolf W (1999) Objective motor response onset detection in surface myoelectric signals. Med Eng Phys 21:449–467 van der Burg JC, Pijnappels M, van Dieën JH (2005) Out-of-plane trunk movements and trunk muscle activity after a trip during walking. Exp Brain Res 165:407–412

van Dieën JH, Pijnappels M, Bobbert MF (2005) Age-related intrinsic limitations in preventing a trip and regaining balance after a trip. Saf Sci 43:437–453

Young JW, Chandler RF, Snow CC, Robinette KM, Zehner GF, Lofberg MS (1983) Anthropometric and mass distribution characteristics of the adult female. Technical Report, FAA Civil Aeromedical Institute, Oklahoma