The role of arm movement in early trip recovery in younger and older adults

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Abstract

The aims of this study were to investigate which arm movements are made during trip recovery, to determine the contributions of arm movements in trip recovery and to identify differences in these contributions between younger and older adults and different recovery strategies. A group of seven older adults (65-75 years) and a group of eight younger adults (20-35 years) were examined. Participants completed a trip recovery protocol in which 3-D kinematic and kinetic data were collected for recovery movements following unexpected trips during locomotion. In younger adults, arm movements were associated with an elevated body centre of mass position during recovery. Arm movements also served to reduce the angular momentum in the direction of the trip by 13% between trip stimulus and recovery foot contact in 'elevating' recovery strategies. Arm movements in older adults contributed an additional 3% to the destabilising angular momentum during 'elevating' recoveries. It was concluded that older adults exhibit a more 'protective' recovery strategy (designed to limit injury resulting from fall impacts following loss of balance) and younger adults exhibit a more 'preventive' strategy (designed to prevent loss of balance).

Keywords

Trip recovery; arm movement; older adults; fall prevention

1. Introduction

Various aspects of the biomechanics of trip recovery have been investigated with a view to understanding more about the movement strategies used by individuals in response to a trip situation. The majority of studies have focussed on response time [1-3], lower limb muscle strength [4, 5] and leg muscle activation variables [6]. It has been found that older people have delayed response reactions which can leave them insufficient time to place their recovery leg in the correct position for successful trip recovery. Pijnappels et al. analysed joint moment and muscle activity patterns of the initial support limb during trip recoveries. They demonstrated that younger adults were generally better able to restrain the forward angular momentum of the body during early recovery by pushing-off with the support limb compared with older adults [6-9]. The direction of forward angular momentum is defined as rotation leading to movement of the body's anterior surface towards the floor.

While most research has focussed on the role of the lower limbs during trip recovery, arm movements might also play an important role in early trip recovery. In theory, appropriate arm movements could lead to an elevation of the whole-body centre of mass (CM) location, providing more time to place the recovery leg in the correct position to counter destabilising influences. Relative backward rotations of the arms could also contribute to counter-acting the whole-body angular momentum in the direction of the trip during early recovery, and therefore reduce the angular momentum which needs to be reversed by the recovery leg following contact with the ground. Allum et al. [10] investigated the extent of arm movements following tilted perturbations to stance and found age-associated changes. Older adults showed arm movements in the direction of the fall, while the younger adults exhibited arm movements that counterbalanced the motion of the pelvis.

In trip recovery the precise role of arm movements may depend on the age of the individual and on the recovery type selected, differing between 'elevating' (perturbed swing leg becomes recovery limb) strategies and 'lowering' (perturbed swing leg set down in front of obstacle and other limb becomes recovery limb) strategies [11].

Therefore, the aim of this study is to determine the contribution made by arm movements during early trip recovery in younger and older adults using different recovery strategies. Our hypothesis was that any arm movements would provide more time for placement of the recovery leg and would be more effective in younger adults.

2. Methods

Participants Healthy, recreationally active females were recruited into one of two groups, a 'younger' group aged 20 to 35 years (n=8), and an 'older' group aged 65 to 75 years (n=7). Participants in the older group were all community-dwelling and were recruited via communication with local community groups. Participant inclusion criteria were a mass-to-body-height ratio below 28, no use of medication that may cause dizziness, no history of repetitive falling and no fear of falling. Good health and absence of fear of falling were demonstrated by answering positive to all questions on a health questionnaire (Par-Q) and returning a score below 0.75 on the SAFFE fear-of-falling questionnaire [12] respectively. An extra inclusion criterion of absence of risk factors for osteoporosis was added for the older group (determined via an NHS referral form for a bone mineral density scan). Participants were provided with an information sheet and signed a written informed consent form. All the experimental procedures were approved by the local NHS research ethics committee.

Group mean characteristics for the younger group were age = 26.1±3.5 years, body mass = 63.2±8.4 kg, height = 1.67±0.04 m, and arm length = 0.64±0.07 m. Group mean characteristics for the older group were age = 70.0±2.5 years, body mass = 64.2±4.8 kg, height = 1.66±0.06 m, and arm length = 0.68±0.01 m.

Experimental protocol Anthropometric measurements were taken to permit determination of segmental inertia parameters using a modified version of the method by Pavol et al. [13]. Following instrumentation, participants were asked to walk in repeated trials at a self-selected pace over a walkway. In 50% of the trials for the younger participants and in 67% of trials for the older participants a trip was induced by a custom-built device. The younger participants completed a total of 100 and the older participants a total of 60 trials. The participants wore glasses (non-corrective lenses) with the lower half obscured to prevent them from seeing when the trip device was activated. A portable music player with inner ear headphones prevented the participants hearing the trip-device being activated. Trips could be induced at various stages of the swing phase and the trip-device was positioned such that contact of the recovery leg was normally made on a force plate embedded in the walkway.

Safety measures The participants were strapped in a full torso safety harness that was attached via elastic ropes to a custom-designed overhead I-beam and trolley system. Participants familiarised themselves with walking in and weighting the harness but trips were not practised prior to trials. Force in series with the harness was measured with a load cell (Kistler Type 9331B, Switzerland) sampling at 1000 Hz to determine unsuccessful recoveries (>30% of body weight). These trials were excluded from the present analysis together with trials with missing data.

Participants wore sport shoes with holes cut in them to allow infra-red emitting diode (IRED) marker placement on the 5th metatarsal and heel. Participants also wore toe protectors and minimally restrictive ankle supports.

Trip-device The trip-device consisted of eight metal plates 0.1m high (four to obstruct the right leg and four to obstruct the left leg) which were spring-loaded and held in a flat position by solenoids. The plates could be released by the operator to obstruct the gait by activating the solenoid which caused the corresponding plate to flip up. The trip-device was attached to a force plate (Kistler 9287BA, Switzerland), which enabled the direct measurement (1000 Hz) of the horizontal impact force acting on the participant's foot and inducing the trip.

Marker setup Three-dimensional (3-D) kinematic data were collected at 200 Hz with the CODA CX1 system (Charnwood Dynamics Ltd., United Kingdom), which was positioned to the left of the walkway. Segmental motions were obtained using a custom triad set-up in combination with the Codamotion segmental gait analysis marker set (Figure 1). In static trials, the relative positions of the joint centres to the triad markers were recorded. For dynamic trials, virtual markers were defined based on this information.

Data analysis The absolute time within a trial that a trip was induced varied. Therefore, all trials were synchronised by defining the time of contact with the trip device as zero. The data were then analysed between -0.25 s and +1.50 s.

The CODA marker positions were smoothed (based on residual analysis, equivalent to cut-off = 39 Hz) and interpolated when necessary using Woltring's B-spline gcvspl matlab routine written by Reina [14] in quintic form. First and second derivatives were calculated without any further smoothing. The smoothed coordinates were combined with segmental inertia characteristics to calculate the CM trajectories of 14 body segments and from this the whole-body CM trajectory was reconstructed.

The 2-D segmental and whole-body angular momentum around the centre of pressure was calculated by the segmental method. The variable 'recovery amount' (RA) was taken as the difference between the maximum angular momentum between the start of the trip and foot contact with the force plate, and the angular momentum at the instant of foot contact with the force plate, to provide an indication of reduction in whole-body angular momentum. The variable 'arm recovery amount' (ARA) was defined as the difference between the maximum and minimum arm angular momentum between the start of the trip and foot contact with the force plate. ARA was used to determine the contribution made by the arms in reducing the destabilising angular momentum in early trip recovery.

The resultant displacement of the CM of the whole arm relative to the body CM was calculated during the early part of trip recovery (between trip stimulus and contact of recovery foot with the force plate) along with its three directional components to indicate the nature of arm movements.

To enable inter-individual comparisons, arm movement was normalised to arm length and RA and ARA were normalised to body weight multiplied by the square of lower limb length (to account for differences in segmental moment of inertia values).

Statistical analysis A successful trip recovery depends on reversal of angular momentum and time to place the recovery limb through raising of the body CM, therefore the variables RA and vertical CM displacement were selected as the dependent variables. This study investigated the influence of arm motions on these outcome measures via the use of arm displacements and ARA as the independent variables. Where appropriate, differences between younger versus older adults, and elevating versus lowering trials were investigated with an unpaired t-test for continuous variables. Associations between continuous variables were investigated using a Pearson Product-Moment correlation. All statistical analyses were performed in SPSS (version 14.0)

3. Results

For the younger group a total of 39 trials were analysed, 14 of which were ‘lowering’ strategy recoveries and 25 ‘elevating’ strategies [11]; for the older group a total number of 33 trials were analysed, 26 of which used a ‘lowering’ strategy and 7 an ‘elevating’ strategy [11]. Elevating and lowering strategies conformed to the definitions by Eng et al. [11].

During early recovery, the vertical displacement of the whole body CM was positively correlated with vertical arm CM displacement of the arm contralateral to the recovery limb ($r = 0.665$, $p < 0.01$) for the younger adults only. Older adults did not exhibit a similar correlation between arm displacement and vertical body CM displacement ($r = 0.091$). However, body CM displacement was not significantly different between younger and older adults for both elevating (younger: 0.09±0.07 leg lengths and older: 0.09±0.04 leg lengths) and lowering recovery strategies (younger: 0.14±0.17 leg lengths and older: 0.15±0.09 leg lengths).

The younger adults moved (resultant displacement) the arm contralateral to their recovery limb more then the older adults in lowering strategy recoveries, 0.48±0.38 arm lengths versus 0.16±0.22 arm lengths ($p<0.05$) (Table 1). Due to large individual variations, no significant differences were found in the extent of arm movement between younger and older adults during elevating strategy trip recoveries (0.22±0.20 arm lengths and 0.04±0.03 arm lengths for the younger and older groups respectively).

The peak velocity of the resultant arm movement in early trip recovery was not significantly different between the younger and older adults (Table 1).

In comparisons between recovery types, the velocity of the ipsilateral arm was higher in lowering than in elevating strategy recoveries for the younger adults. The younger adults also showed a larger displacement of the contralateral arm in lowering than in elevating strategies (Table 1).

Considering the directional components of the arm motions, in lowering strategy recoveries the younger adults showed larger lateral displacement than older adults for both arms (0.17±0.12 and 0.11±0.05 arm lengths versus 0.10±0.09 and 0.07±0.05 arm lengths [$p < 0.05$] for the ipsi and contralateral arms respectively), and larger anterior displacement in the arm ipsilateral to the recovery limb (Figure 2b). Arm movement in elevating strategy recoveries were not significantly different between the younger and older adults (Figure 2a).

The older adults showed a relatively larger anterior arm movement in relation to the vertical movement than the younger adults in early trip recovery. For elevating strategy recoveries, the vertical arm displacement of the younger adults was 125% and 65% of the anterior displacement for the arm ipsilateral and the arm contralateral to the recovery limb respectively, while they were 58% and 29% for the older adults. For lowering strategy recoveries the vertical arm displacement of the younger adults were 106% and 65% of the anterior displacement for the arm ipsilateral and the arm contralateral to the recovery limb respectively, while they were 69% and 58% for the older adults.

In elevating strategies the Arm Recovery Amount (ARA) magnitude of the contralateral arm was a larger percentage of overall body Recovery Amount (RA) in the younger (13.0%) than in the older adults (-2.8%). This percentage was positive in the younger adults and negative in the older adults (Table 2), which means arm movement helped to reduce the forward angular momentum of the body in the younger adults while in the older adults, arm movements increased the forward angular momentum. This percentage was not significantly different between the younger and the older adults during lowering strategy recoveries. ARA of the older adults was significantly different between elevating (7.8%) and lowering (-2.8%) strategy recoveries.

4. Discussion

During both elevating and lowering strategy recoveries younger subjects exhibited the largest arm movement in the arm contralateral to the recovery limb. This arm was moved forward and lifted upwards, giving it a backward swing movement relative to the trunk. This movement counter-balanced the motion of the recovery limb in a similar way as can be seen by arm swing in walking or running. Laterally, the arms initially moved away from the body before returning to their original position. This lateral displacement would increase the moment of inertia about the frontal axis during early recovery and provide extra lateral stability by minimising rotations in this plane during the initial phases of the recovery. This suggests that the younger adults used a coordinated arm movement to help maintain balance and to assist in actual recovery from the trip situation.

Vertical arm movement was positively correlated with the body CM displacement in elevating strategies of the younger adults only ($r = 0.665$). This elevation of the body CM from greater arm motion is likely to provide extra time for placement of the recovery limb. The body CM displacement during early trip recovery was however not significantly different between the younger and older adults. This suggests that the older adults elevated their body CM by other means, possibly through larger relative joint torques in the initial support limb, although it has been previously suggested that younger people have the greater capacity to use this strategy [9].

Arm movement also appeared to play a role in reducing the forward angular momentum of the body during elevating (13.0%) and lowering strategy recoveries (9.1%) in the younger adults. The contribution of the arm movements for older adults was -2.8% for elevating recovery strategies and 7.8% for lowering strategies. Therefore, a relative backward motion of the arms can be seen to make an important contribution to the reversal of the induced angular momentum during early trip recovery (prior to contact of the recovery limb). These contributions will support the contributions made by the initial support limb as demonstrated previously by Pijnappels et al. [7-9].

Increased arm motion for younger compared with older adults was mainly in the vertical direction in elevating strategy recoveries and in the lateral direction in lowering strategy recoveries. The older adults exhibited a lower ratio of vertical to anterior arm displacement, resulting in a reaching arm movement, while the younger adults had a lifting arm movement, in both elevating and lowering strategy recoveries. This agrees with findings by Allum et al. [10] in perturbations induced during quiet stance. The reaching movement of the older adults suggested that they were anticipating an unsuccessful recovery and reached forward to protect themselves against a potential fall, rather than using their arms to make an attempt to recover balance. It has to be emphasised that the younger and older adults had similar scores on the fear of falling questionnaire and showed no presence of fear of falling.

Inter-individual variation was high in this study as can be seen by the high standard deviations in arm displacement (Table 1) and ARA (Table 2). Pijnappels et al. [7] also found a high inter-individual variation in their study of the reduction of the forward angular momentum of the body by the initial stance limb. Not all their subjects were able to reduce the angular momentum during the push off phase of the support limb in the same way as not all subjects in this study used their arms to the same extent within groups. Further research is required to investigate the reasons for this high inter-individual variation and to investigate why some people of similar age and anthropometric characteristics are able to recover from trips more successfully than others.

It can be concluded from this study that arm movements play a contributing role in trip recovery in younger adults by elevating the body CM and reducing the forward angular momentum of the body, both providing more time for appropriate positioning of the recovery limb. The older adults showed a more protective arm response, reaching forward to arrest a possible fall, which limited the contribution which could be made by the arms to raise body CM and reverse angular momentum. Future research is required to investigate whether older adults will benefit from a more preventive arm movement similar to that of younger adults.

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Captions to illustrations

Figure 1

The placement of the CODA markers for trip recovery trials.

Figure 2

Maximum arm CM displacement in lateral, anterior and vertical direction for elevating (a) and lowering (b) recovery strategies. Significant differences (independent t-test, $p<0.05$) between the younger and older group are indicated with *.

Tables

Table 1

Maximum resultant arm CM displacement and peak resultant arm velocity during early trip recovery. Significant differences (independent t-test, $p<0.05$) between the younger and older groups are indicated with * and significant differences between elevating and lowering strategy recoveries with $^{\&}$.

		Ipsilateral arm		Contralateral arm	
		Displacement (arm lengths)	Velocity (arm lengths/s)	Displacement (arm lengths)	Velocity (arm lengths/s)
Elevating	Younger	0.04±0.07	0.39±0.42	0.22±0.20	0.40±0.40
	Older	0.12±0.07	0.66±0.40	0.04±0.03	0.44±0.37
Lowering	Younger	0.17±0.37	0.91±0.71$^{\&}$	0.48±0.38$^{\&}$	0.58±0.49
	Older	0.14±0.18	0.72±1.24	0.16±0.22*	0.61±0.58

Table 2

Average arm recovery amount of the arm contralateral to the recovery limb. Significant differences (independent t-test, $p<0.05$) from the younger group are indicated with * and significant differences between elevating and lowering strategy recoveries with [&].

	Arm recovery amount percentage	
	Elevating	Lowering
Younger	13.0±12.5%	9.1±9.1%
Older	-2.8±0.6%*	7.8±6.4%[&]

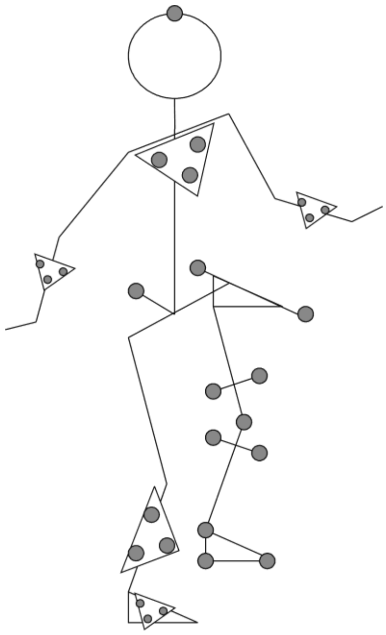


Figure 1

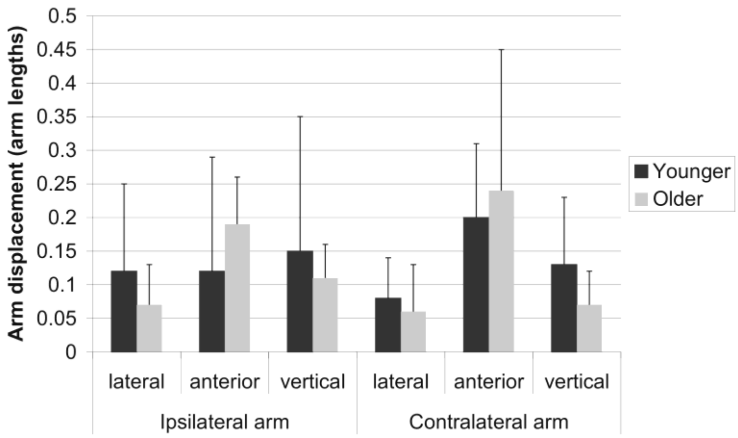
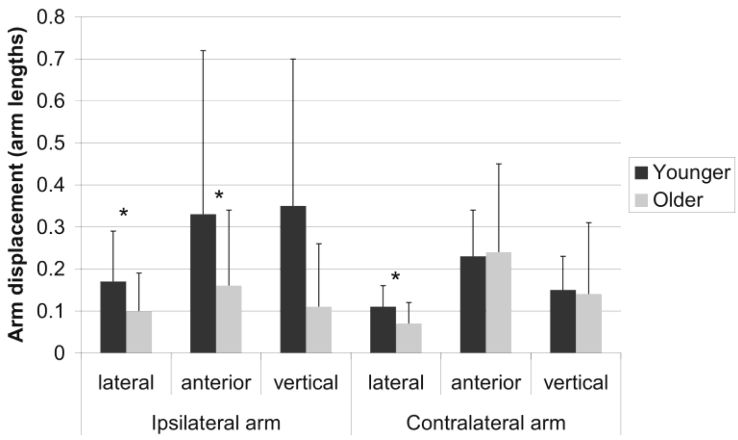


Figure 2a



Arm displacement (arm lengths)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
*
*
*
Younger
Older
lateral
anterior
vertical
lateral
anterior
vertical
Ipsilateral arm
Contralateral arm

Figure 2b