Older adults who have previously fallen due to a trip walk differently than those who have fallen due to a slip

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Abstract

Studying the relationships between centre of mass (COM) and centre of pressure (COP) during walking has been shown to be useful in determining movement stability. The aim of the current study was to compare COM-COP separation measures during walking between groups of older adults with no history of falling, and a history of falling due to tripping or slipping. Any differences between individuals who have fallen due to a slip and those who have fallen due to a trip in measures of dynamic balance could potentially indicate differences in the mechanisms responsible for falls. Forty older adults were allocated into groups based on their self-reported fall history during walking. The non-faller group had not experienced a fall in at least the previous year. Participants who had experienced a fall were split into two groups based on whether a trip or slip resulted in the fall(s). A Vicon system was used to collect full body kinematic trajectories. Two force platforms were used to measure ground reaction forces. The COM was significantly further ahead of the COP at heel strike for the trip (14.3±2.7cm) and slip (15.3±1.1cm) groups compared to the non-fallers (12.0±2.7cm). COM was significantly further behind the COP at foot flat for the slip group (-14.9±3.6cm) compared to the non-faller group (-10.3±3.9cm). At mid-swing, the COM of the trip group was ahead of the COP (0.9±1.6cm), whereas for the slip group the COM was behind the COP (-1.2±2.2cm). These results show identifiable differences in dynamic balance control of walking between older adults with a history of tripping or slipping and non-fallers.

Key words; gait, postural stability, elderly fallers, locomotion, movement control

1. Introduction

Falls and fall-related injuries are among the most serious and common medical problems experienced by the older population with approximately 28% of community-dwelling older adults experiencing at least one fall a year [1]. The majority of falls (over 60%) in this age group are in the forward direction [2], and 53% of falls [3] and 20% of hip fractures [4] are reported as the result of a trip. In non-fatal falls, almost half of all fallers are unable to get up without help [5], and nearly one-third of falls in community dwelling older adults have been reported to produce pain lasting for 2 or more days [6]. As most falls occur during locomotion [7], it is important to develop a greater understanding of gait and the underlying control mechanisms that govern stability during movement.

Slips and trips are associated with different phases of the gait cycle. Slips are most likely to occur shortly after heel strike when only the edge of the heel is in contact with the ground or during toe off when only the forepart of the shoe is in contact with the ground [8]. Of these occurrences, forward slips occurring at heel strike are the most challenging type of slip for both young and older adults to recover from and avert a fall [9]. Trips occur during the swing phase of the gait cycle, and the recovery mechanism employed varies with the timing of the perturbation. An elevating strategy occurs in early to mid-swing, where the perturbed limb is lifted over the obstacle, whereas a lowering strategy occurs in late swing where the perturbed limb is placed prior to the obstacle and the contralateral limb is lifted over. Some older adults use a lowering rather than an elevating strategy when perturbed in the mid swing phase [10], suggesting that a less appropriate response for trip recovery is employed in these individuals at the phase of the gait cycle [11]. It has also been observed that trip perturbations during late-mid and late swing are most likely to result in falls in older adults [11].

Previous studies have demonstrated the usefulness of the centre of mass-centre of pressure (COM-COP) interaction as a measure of stability during locomotion [12, 13]. The COM is in a state of dynamic balance during walking, with the COP moving behind and then ahead of the COM in the sagittal plane, resulting in the total body gravity force vector passing forward through the COP four times in one gait cycle [12]. Peak anterior COM-COP separation was decreased in older people compared with young adults [13] possibly indicating a conservative strategy to reduce the mechanical load on the supporting limb. However, anterior COM-COP separation increased in hemiparetic patients when the stance limb was on the affected side [14], suggesting that maintaining balance on the affected side was a greater challenge to stability. A recent study suggests that incorrect weight shifting resulting in the COM being moved beyond their base of support was the main reason for falling in care home residents [15]. Investigating COM-COP separation at points in the gait cycle associated with slips and trips may provide further information on postural stability during walking in older adults. Any differences between individuals who have tripped and those who have slipped in measures of dynamic balance could potentially indicate differences in the mechanisms responsible for falls. The aim of this study was to investigate differences in COM-COP separation measures during walking in groups of older adults without a history of falling and with a history of tripping or slipping resulting in a fall.

2. Methods

2.1 Participants

Forty community-dwelling older adults were recruited to the study from the local area through links with retirement groups. Ethical approval for the research was granted through institutional procedures conducted at departmental level. All participants gave written informed consent prior to data collection, and the study was carried out in accordance with the principles laid down by the Declaration of Helsinki. All of the older participants were able to walk at least 100 m without the use of a gait aid, and reported themselves free of any neurological disease, head trauma, musculoskeletal impairment and visual impairment not correctable by lenses. A falls questionnaire was completed which asked participants whether they had experienced a fall, which was defined as a loss of balance resulting in the body, or part of the body, coming to rest on the ground [16] and how many times this occurred. Participants were also asked to indicate how they fell on each occasion by ticking a box next to the categories: trip, slip, unsure, felt faint/dizzy. Participants were then interviewed about each fall prior to testing. Examples of response recorded were "I caught my toe on the pavement" for a trip and "my foot slid forward" for a slip. Participants were generally very clear about whether they thought they had slipped or tripped. Each report of a fall was discussed at the lab testing session prior to data collection starting in which we also checked if any falls had occurred between questionnaire completion and data collection. Of the "slip" group, four participants reported one fall and six participants reported two falls in the year before testing. Of the "trip" group, seven participants reported one fall, six reported two falls and one participant reported three falls.

Any participant who could not clearly recollect details of the fall or reported both a slip and a trip were excluded from the study.

This manuscript presents retrospective analysis of data collected as part of a larger study investigating the relationships between lifelong physical activity and biomechanical measures of stability in a group of older adults. Therefore the number of participants in each group was randomly determined. The participants were split into three groups based on their self-reported previous fall history during walking. The non-faller group (n=16, 10 female, age 72±5 years, height 166.6±8.2 cm, mass 68.1±9.4 kg) had not experienced a fall in at least the 12 month period prior to testing. Participants who had experienced at least one fall in the 12 months prior to testing were split into two groups based on whether a trip (n=14, 10 female, age 71±6 years, height 164.9±9.6 cm, mass 71.5±14.0 kg) or slip (n=10, 6 female age 68±5 years, height 169.8±9.3 cm, mass 76.0±18.2 kg) had resulted in the fall.

2.2 Data collection

Whole body motion data were collected at 60 Hz using a 14-camera Vicon MCam2 system (Vicon Peak, Oxford Metrics Ltd., UK) set up in a large (17 x 12 x 4.5 metres) gait laboratory. The full-body Vicon Plug-in Gait (PiG) marker set was used. Ground reaction forces were collected by two force platforms (AMTI BP400600NC, Watertown, USA), placed in series and embedded in the floor of the laboratory with their top surface flush with the laboratory floor. The force platforms were situated in the centre of the laboratory, therefore were in the middle of the walkway used during testing. The force platform data were captured at 120 Hz and time-synchronised to the motion capture system.

Participants were instructed to walk at their self-selected velocity across the laboratory. The participants were not given instructions on foot placement across the force platforms, so that they would not alter their stride pattern to strike the force platforms. Walking trials were conducted until there were three trials with clean foot strikes on both force platforms. Most participants achieved this within three or four trials: the maximum number of trials needed was six.

2.3 Data analysis

Vicon Workstation software (Vicon Peak, Oxford Metrics Ltd., UK) was used to reconstruct the data from each camera into three-dimensional trajectories. Data were filtered using a 2nd order, multi-pass Butterworth filter with a cut-off frequency of 10 Hz. The first and last strides were not included in analysis since we were interested in studying steady state walking rather than gait initiation and termination.

The position of the whole body COM was computed in Vicon Bodybuilder software (Vicon Peak, Oxford Metrics Ltd., UK) using a model based on Vicon's Golem model. Whole body COM was the weighted sum of each body segment's COM using a 13-link biomechanical model. COP data were combined from both force platforms to provide a single COP:

$$COP = COP_1 \frac{Fz_1}{Fz_2 + Fz_1} + COP_2 \frac{Fz_2}{Fz_1 + Fz_2}$$

where COP_1 and COP_2 are the COPs on the 2 separate force platforms and Fz_1 and Fz_2 are the vertical ground reaction forces on force platform 1 and force platform 2.

The horizontal distance between COM and COP was calculated for in both the antero-posterior (AP) and medio-lateral directions. AP and ML COM velocity were also calculated. Values were determined for 5 points across the gait cycle (GC): heel strike, foot flat, toe off, mid-swing and late swing. Foot flat was defined as the instant where the toe marker reached its first minimum vertical position after heel strike [8]. Mid-swing was defined as 50% and late swing as 90% of the swing phase. Peak braking force and peak propulsive force were calculated from the AP component of the ground reaction force, and scaled to body weight (BW). The percentages of the gait cycle where these peaks occurred were also detected. Differences between groups in these variables were investigated using a one-way ANCOVA with height as a covariate. Although there were no significant differences between groups for height ($p=0.419$), height was added as a covariate for the analysis as the COM-COP variable may be influenced by stature [17]. *Post hoc* analysis was conducted with a Bonferroni test to identify the location of any differences. Level of significance was set at $p = 0.05$.

3. Results

There were no significant differences between groups for walking speed, stride time, stride length, M/L COM-COP, A/P or M/L COM velocity or peak braking and propulsive forces at any point in the gait cycle (see Table 1).

****INSERT TABLE 1 ABOUT HERE****

The general pattern of COM-COP separation across the gait cycle was similar for all participants (see Figures 1B-1D for representative data from a participant from each group). At heel strike, the COM was close to or at its most anterior position with respect to the COP. During double support, there was a rapid shift of the COP from the trailing foot to the leading foot resulting in the COM being posterior to the COP at toe off of the contralateral limb. During single support, the COM moved anteriorly with respect to the COP as the body progressed forward in preparation for the next heel strike.

Although the general pattern of COM-COP separation was similar, group differences were detected at three specific points of the step cycle. These are highlighted by the grey circles in figures 1B-1D

There was a significant main effect of group on COM-COP at heel strike ($F_{(2, 36)} = 6.46$, $p = 0.004$). Pairwise comparison revealed that the COM was significantly further ahead of the COP at heel strike for the trip and slip groups compared to the non-fallers (see Figure 2A).

There was also a significant main effect of group on COM-COP at foot flat ($F_{(2, 36)} = 4.29$, $p = 0.021$). Pairwise comparison revealed that COM was significantly further behind the COP at foot flat for the slip group compared to the non-fallers (see Figure 2B).

There was also a significant main effect of group on COM-COP at mid swing ($F_{(2, 36)} = 3.28$, $p = 0.049$). Pairwise comparison revealed the COM of slip trip group was significantly further behind the COP at mid swing compared to the trip group (see Figure 2C).

****INSERT FIGURE 2 ABOUT HERE****

Although we found no significant group differences in stride length there was a non-significant trend for larger stride length in the slip group (mean difference 9cm – see Table 1). In an attempt to further elucidate the mechanisms underlying the differences in observed COM-COP dynamic relationships we carried out correlation analysis between stride length and our measures of COM-COP that produced significant group differences and found significant relationships between stride length and COM-COP separation at heel contact ($r^2 = 0.61$, $P < 0.0001$) and foot flat ($r^2=0.19$, $P = 0.005$). Therefore variability in COM-COP dynamics that differed between groups was strongly associated with variability in stride length.

4. Discussion

The findings from this study show differences in COM-COP kinematics across the gait cycle between community-dwelling older adult fallers and non-fallers, and between individuals grouped on the basis of whether they fell because they either tripped or slipped. This is the first study to identify kinematic differences between older adults grouped in this way. This is apparent at heel strike, where both the trip and slip group placed their COM in a more anterior position with respect to their COP than the non-faller group. COM was significantly further behind the COP at foot flat for the slip group compared to the non-fallers. At the mid-point of the swing phase, the COM for the trip group was ahead of the COP, whereas for the slip group the COM was still positioned posterior to the COP.

Trip perturbations during late-mid and late swing are reported to most likely result in falls in older adults [11]. A more anterior placed COM provides a greater challenge to stability and increases the chance of a fall in the forward direction [18]. This is due to resulting larger external flexion moments about the joints in the stance limb, increasing the demand for resistive muscular force generation [19]. Even in high-functioning, physically active older adults, a perturbation during walking results in an initial destabilisation period 25% longer and re-stabilising the COM takes longer than for young adults [20]. Therefore, the trend towards a more anterior COM placement at late swing and a significantly more anterior COM at heel strike in this older adult trip group may indicate that these individuals are less able to recover from a perturbation during this phase of the gait cycle.

Older adults make the transition to a lowering strategy for trip recovery earlier in the swing phase than young adults [11], and this strategy selection is associated with lower recovery success in tripping studies [10]. A lowering strategy results in a larger disruption to the COM trajectory and an increased initial response duration compared to an elevating strategy [20]. In the current study, the trip group appeared to position their COM more anteriorly with respect to the COP than either the non-faller or slip group (significantly different). A more anterior COM makes an elevating strategy more difficult for balance recovery as larger forces are required in the recovery limb [11]. Further research could investigate whether the position of the COM at this phase of the gait cycle is related to a preference for a lowering rather than an elevating strategy in some older adults in response to a trip during mid-swing.

In terms of the slip group, the finding that the COM was significantly more anterior to the COP at heel strike is surprising. It has been suggested previously that rapidly placing the recovery foot posterior to the COM is necessary to prevent a fall after slipping [21]. A more anteriorly positioned COM at this phase of the gait cycle would therefore be expected to be beneficial for this recovery strategy. However, when walking on a slippery surface, the placement of the recovery foot posterior to the COM was not translated into a successful recovery from a slip at heel strike [22]. This may be due to recovery responses differing between slips initiated by a slipping platform and those by a slippery surface, with slips due to the surface thought to be more representative of those that occur in the community [23]. The use of upper extremity motion to reduce trunk extension during slipping may be more beneficial for avoiding a fall than the positioning of the COM to the base of support at slip onset [24]. As slips are explosive and ballistic in nature [25], other factors such as muscle strength and onset latencies may be of greater importance than COM positioning for whether a recovery is successful or not.

Our results show that the differences between the slip group and the trip group in mean COM-COP separation at foot flat is around 5cm which represents around a 50% increase. A recent paper by Yamaguchi et al (2013) suggests that COM and COP kinematics serve as a predictor of friction requirement during the weight acceptance and push-off phases in steady-state movements such as straight walking and transient movements such as turning as well as gait termination and initiation. A greater COM-COP distance during late stance increases the required coefficient of friction and therefore increases the risk of a slip [26]. A more posteriorly aligned COM at this phase of the gait cycle has been linked with falling rather than recovery of a slip perturbation [27]. Therefore, the positioning of the COM in the slip group at this phase of the gait cycle may place these individuals at greater risk of falling in response to a slip than either the non-faller or trip group.

The results of our correlation analysis suggests that the variability in COM-COM separation at both heel strike and late stance (foot flat) can be partially explained by variability in participant stride length which tended to be greater in the slip group than the two other groups (although non-significant). However, it is likely that a combination of different gait kinematic variables are responsible for the observed changes in COM-COP relationships and we were not able to elucidate these fully in this initial retrospective study.

There were no significant differences between groups for any of gait speed, cadence, stride length, stride width, peak braking or propulsive forces, or the point in the gait cycle where these peaks occur. In combination, these lack of differences suggest that previous experience of falling did not result in a cautious gait pattern in the participants in this study. Therefore, it is unlikely that group differences in COM-COP kinematics observed are a result of walking more cautiously.

In terms of practical application of these research findings, previous research has suggested that older adults can benefit from training sessions to avoid falling from a trip [29] or slip [30]. In young adults, trip training resulted in adjustments to the COM position and velocity both proactively and reactively [18]. Therefore, if differences in COM-COP kinematics can be linked to the risk of falling from a trip or slip, these older adults can be targeted with appropriate training to reduce the risk of experiencing a fall from these types of perturbation.

Limitations

Retrospective studies, such as those conducted here, are weaker than prospective studies in predicting future falls as differences detected between falls groups were not detected prior to a fall. However, the differences between groups detected in the current study do not indicate a more conservative balance strategy adopted by either of the faller groups in response to their previous falls experiences compared to the non-faller group. This paper did not investigate tripping or slipping directly, however, or the recovery from either type of perturbation therefore, conclusions cannot be drawn that COM-COP separation differences between the groups led to the fall events that had been experienced by some participants. Indeed, we accept the possibility that circumstances may generally affect the type of fall encountered more than gait parameters do; for example, it is expected that more falls due to slips would occur during cold winter months due to environmental conditions. Furthermore, it is hard to disentangle the confounding influence of number and the nature of falls experienced by each participant and therefore we need to exercise caution in classifying our participants as those who trip and those who slip. Nevertheless, we have identified specific walking behaviour in a group of older adults who have slipped over in the past likely to increase their risk of slipping in the future. We believe that this finding is important and the underlying mechanisms need further investigation.

Another limitation of the current study is the small sample size of participants which although sufficient to identify significant differences in A/P COM-COP relationships is probably inadequate to identify more subtle group-related differences in gait kinetics and kinematics and the complex relationships between the numerous gait variables responsible for the observed differences. Nevertheless, statistically significant differences in behaviour between the groups were identified, and we believe these differences warrant further research to investigate whether these behaviours are present prior to falling and whether they are linked to the type of fall event.

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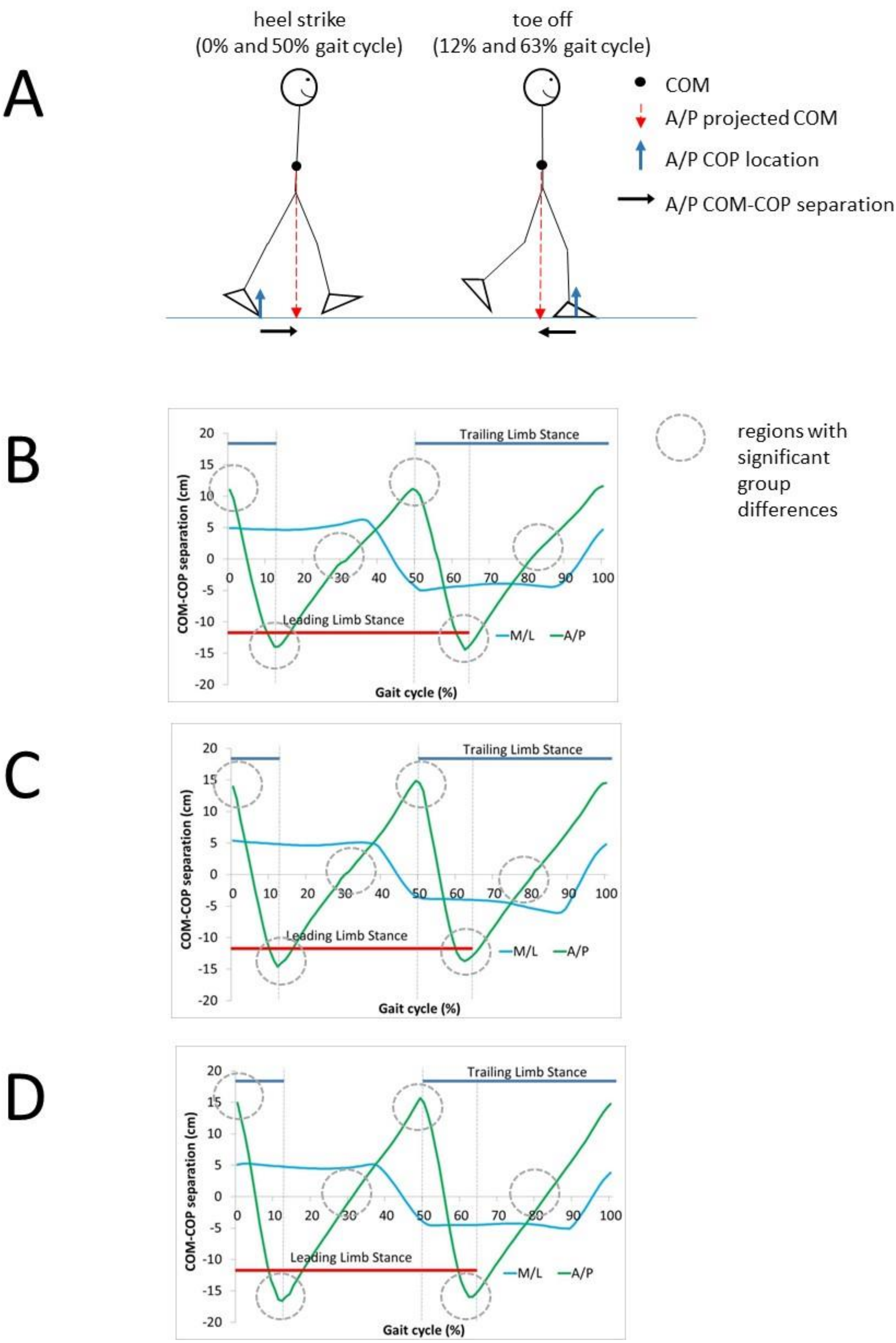
Table 1. Gait parameters for the three groups.

	Non Fallers (n=16)	Trip (n=14)	Slip (n=10)	p
Walking speed ($m.s^{-1}$)	1.14 ± 0.13	1.19 ± 0.20	1.22 ± 0.14	0.459
Stride time (s)	1.10 ± 0.10	1.06 ± 0.08	1.10 ± 0.10	0.614
Stride length (m)	1.26 ± 0.14	1.26 ± 0.17	1.34 ± 0.09	0.484
COM-COP at toe off (cm)	-14.3 ± 1.7	-15.1 ± 2.5	-16.5 ± 2.2	0.069
COM-COP at late swing (cm)	11.0 ± 2.7	13.4 ± 3.8	13.2 ± 2.4	0.058
Peak braking force (%BW)	-15.1 ± 3.2	-15.9 ± 4.0	-16.5 ± 3.9	0.623
Instant of peak braking force (%GC)	10.9 ± 1.5	10.8 ± 2.2	11.2 ± 0.8	0.795
Peak propulsive force (%BW)	17.1 ± 4.0	17.3 ± 3.6	19.3 ± 2.9	0.237
Instant of peak propulsive force (%GC)	54.3 ± 1.5	54.0 ± 1.9	54.1 ± 1.0	0.826

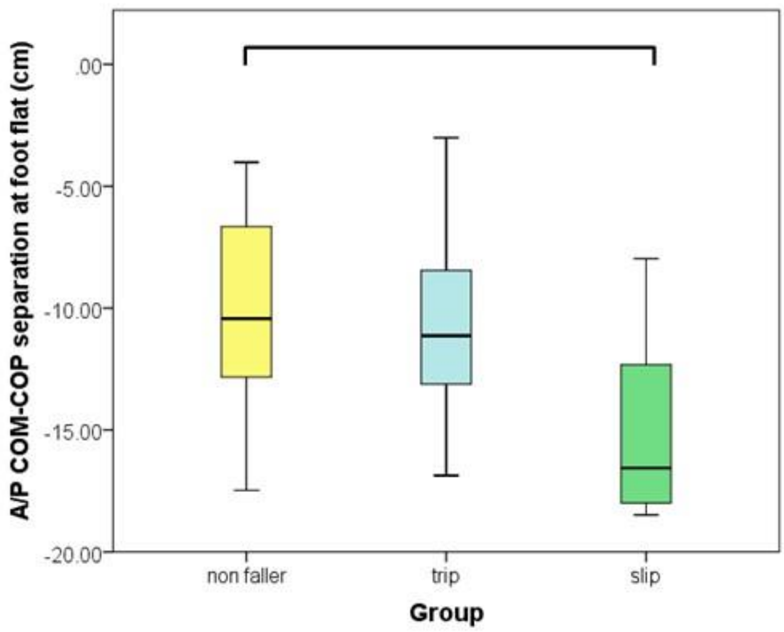
Figure 1. Illustration of the COM-COP separation measures and how they changed across the gait cycle. Figure 1A shows the relative positions of the COM and COP at toe off and heel strike. Figures 1B-1D show representative data from a participant from the non-fallers, trip and slip groups respectively.

Figure 2A-C. Boxplot to compare COM-COP separation between the three groups heel strike (A), foot flat (B) and mid swing (C). The box of the plot encloses the middle half of the sample, with an end at each quartile. The length of the box is thus the interquartile range of the sample. A line is drawn across the box at the sample median. Whiskers sprout from the two ends of the box until they reach the sample maximum and minimum. The black horizontal lines linking group data indicates statistically significant differences between those groups.


A
heel strike
(0% and 50% gait cycle)
toe off
(12% and 63% gait cycle)
COM
A/P projected COM
A/P COP location
A/P COM-COP separation
B
regions with significant group differences
Trailing Limb Stance
Leading Limb Stance
COM-COP separation (cm)
Gait cycle (%)
M/L
A/P
20
15
10
5
0
-5
-10
-15
-20
0
10
20
30
40
50
60
70
80
90
100
C
Trailing Limb Stance
Leading Limb Stance
COM-COP separation (cm)
Gait cycle (%)
M/L
A/P
D
Trailing Limb Stance
Leading Limb Stance
COM-COP separation (cm)
Gait cycle (%)
M/L
A/P

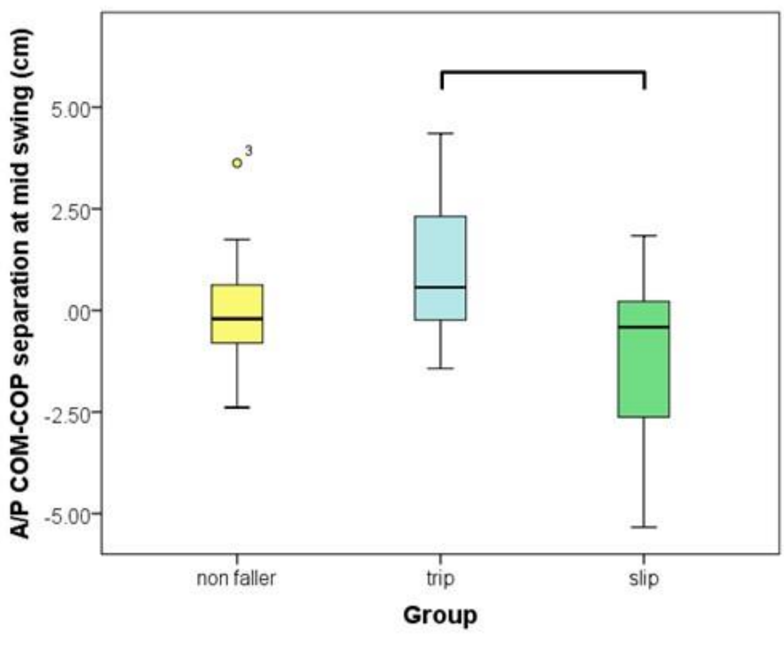
A

B



A/P COM-COP separation at foot flat (cm)
.00
-5.00
-10.00
-15.00
-20.00
non faller
trip
slip
Group

C



A/P COM-COP separation at mid swing (cm)
5.00
2.50
.00
-2.50
-5.00
3
non faller
trip
slip
Group

Highlights

- COM-COP separation was compared between different older adults faller groups
- COM-COP separation was greater at heel strike for fallers than non-fallers
- COM passed ahead of COP earlier in the swing phase for the trip group
- Results have implications for falls prevention and treatment