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Age-related changes in gait adaptability in response to unpredictable obstacles and stepping targets

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ABSTRACT

Background: A large proportion of falls in older people occur when walking. Limitations in gait adaptability might contribute to tripping; a frequently reported cause of falls in this group.
Objective: To evaluate age-related changes in gait adaptability in response to obstacles or stepping targets presented at short notice, i.e.: approximately two steps ahead.
Methods: Fifty older adults (aged 74 ± 7 years; 34 females) and 21 young adults (aged 26 ± 4 years; 12 females) completed 3 usual gait speed (baseline) trials. They then completed the following randomly presented gait adaptability trials: obstacle avoidance, short stepping target, long stepping target and no target/obstacle (3 trials of each).
Results: Compared with the young, the older adults slowed significantly in no target/obstacle trials compared with the baseline trials. They took more steps and spent more time in double support while approaching the obstacle and stepping targets, demonstrated poorer stepping accuracy and made more stepping errors (failed to hit the stepping targets/avoid the obstacle). The older adults also reduced velocity of the two preceding steps and shortened the previous step in the long stepping target condition and in the obstacle avoidance condition.
Conclusion: Compared with their younger counterparts, the older adults exhibited a more conservative adaptation strategy characterised by slow, short and multiple steps with longer time in double support. Even so, they demonstrated poorer stepping accuracy and made more stepping errors. This reduced gait adaptability may place older adults at increased risk of falling when negotiating unexpected hazards.

1. Introduction

The ability to adjust gait is crucial when performing daily living activities such as crossing a busy street or avoiding obstacles. In older age, limited sensorimotor and cognitive functions [1] may lead to poor gait adaptability which might contribute to tripping; a frequently reported cause of falls in this group [2].

Obstacle negotiation tests have previously been used to measure gait adaptability performance. Compared with young, older adults initiate adjustments in step length and step time one or two steps earlier when approaching a fixed obstacle [3] and display shorter step lengths, slower gait speed and smaller obstacle-heel distance when crossing an obstacle [4]. In addition, gait protocols involving the sudden-appearance of an obstacle on a treadmill reveal that older adults have longer avoidance reaction times, larger toe clearances [5] and lower obstacle avoidance success rates compared with young adults [5,6]. Adaptive gait experiments have also found that compared with young, older adults were less accurate when stepping on targets [7] and made slower stepping adjustments to visual target moving to unpredictable locations [8].

More recent research has used stepping paradigms including an inhibitory component [6,9,10] that may reflect the cognitive load challenges required for walking in many daily life situations. Yamada et al. [10] used an overground multi-target stepping task which required participants to step on squares with an assigned colour while avoiding other coloured squares and demonstrated

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that stepping failures were associated with an increased risk of falling. However, the target panels were present at all times so participants were able to pre-plan their stepping trajectories. This limits the ability to draw conclusions about an individual's ability to adapt gait in response to changes in the pathway. Response inhibition has also been incorporated in a treadmill stepping test [6,9] requiring precision steps and avoidance of obstacles. This research showed that shorter available response time contributes to increased stepping failures [9] with the largest failure rates occurring when participants had to perform a secondary inhibitory task [6]. Although these studies provide good insights into adaptive gait failures, no studies have investigated gait adaptation strategies during an over-ground walking task combining both precision steps and obstacle avoidance.

We, therefore, devised an overground walking task that assessed the ability to adapt gait in response to obstacles and targets appearing on the walkway two steps ahead of the individual. Walk-through trials in which no stimulus appeared (catch trials) were included as a way to estimate the extent of the effects of expectation of a gait perturbation. Our aim was to compare the gait adaptability strategies of young and older adults when performing this task. We hypothesised that compared with young, older adults would (a) make more mistakes and demonstrate lower accuracy in negotiating the targets/obstacle, and/or (b) use a more cautious/conservative strategy when approaching the targets/obstacle.

Table 1
Anthropometric, physiological and neuropsychological characteristics of young and older groups.

Variables	Younger adults Mean ± SD, $n = 21$	Older adults Mean ± SD, $n = 50$
Age (years)	26 ± 4	74 ± 7
Number of women	12	34
Body mass (kg)	72.0 ± 17.2	71.1 ± 15.4
Body height (cm)	170.7 ± 10.2	165.4 ± 10.7
Leg length (cm)	88.8 ± 6.1	90.6 ± 5.8
Edge contrast sensitivity (dB)[a]	24.3 ± 2.1	20.5 ± 3.0[g]
PPA fall risk score[b]	−0.6 ± 0.8	1.2 ± 1.0[g]
TMT score (s)[c]	33.6 ± 15.1	55.3 ± 39.7[g]
MoCA score[d]	N/A	26.3 ± 2.6
Icon-FES score[e]	N/A	45.2 ± 13.5
Previous falls (%)[f]	N/A	34

[a] Melbourne Edge Test, score range 0–26, low scores indicated impaired performance.
[b] Physiological Performance Assessment, includes measures of vision (contrast sensitivity), hand reaction time, postural sway, proprioception and leg muscle strength (PPA fall risk is designated mild if the score is between 0 and 1, moderate between 1 and 2, and marked for scores >2).
[c] Trail Making Test, time difference between part B and part A, high scores indicated impaired performance.
[d] Montreal Cognitive Assessment, scores ≥26 indicate intact cognition.
[e] Iconographical-Fall Efficacy Scale, indicating low-moderate concern of falling.
[f] Percentage of participants that reported falling once or more in the previous 12 months.
[g] Significantly different between young and older groups ($p < 0.05$).

2. Methods

2.1. Participants

Fifty older adults aged 65 years and older and twenty-one young adults took part in this study. Anthropometric, neuropsychological and physiological function scores for the young and older groups are presented in Table 1. Older participants were recruited from Neuroscience Research Australia's (NeuRA) volunteer database. Younger participants were NeuRA employees or university students. All participants were living independently in the community and were able to walk 20 m without assistance and cognitively capable to follow all instructions. Exclusion criteria were: insufficient English language skills, colour-blindness; neurological, musculoskeletal or cardiovascular impairment affecting the assessments. The study was approved by the University of New South Wales Human Research Ethics Committee and participants provided informed consent prior to participation.

2.2. Protocol

Participants attended NeuRA on one occasion where they performed a brief neuropsychological [11,12] and physiological assessment [13] as well as the gait adaptability test. Older participants were also asked about any falls suffered in the past year and their concern about falling [14].

2.3. Gait adaptability test

Initially, participants were required to walk at self-selected speed over a 6 m obstacle-free path (baseline-walking condition). They were then instructed about the gait adaptability test and completed walking trials in four experimental conditions: (i) avoid stepping on a pink stimulus positioned two steps ahead (obstacle avoidance); (ii) stepping onto a green stimulus positioned slightly short of two steps ahead (short target); (iii) stepping onto a green stimulus positioned slightly further than two steps ahead (long target); (iv) walking with no stimulus appearing on the pathway (walk-through). Walk-through trials were included to encourage participants to walk naturally [15–17]. The main difference between the baseline-walking and walk-through conditions was probability of stimulus appearance (75% for the walk-through condition and 0% for baseline). Trials were presented in a completely randomised order. Participants performed three trials per condition and at least one practice trial per experimental condition before data acquisition or until the experimenter was certain that the task was understood.

The target/obstacle consisted of a coloured light stimulus projected on a 215 mm × 215 mm area on the walkway presented on the third heel strike following gait initiation and positioned at two-step ahead of the participant at the time of presentation (Fig. 1). The target/obstacle size and shape was chosen to ensure that (a) the targets/obstacles were long enough (approximately a third of step length) so that participants would have to adjust their stepping pattern in the anterior–posterior plane and (b) not too long or wide so that participants would be unable to step over or around them. Participants were instructed to step in the middle of the targets and to avoid stepping on the obstacle, being free to use any avoidance strategy.

For the purpose of comparing stepping strategies, the step that hit or avoided the stimulus was named "target/obstacle step" and the preceding step was named "previous step". Outcome measures were: (i) number of incorrect responses to the stimulus (stepping on an obstacle or missing a target), (ii) number of steps taken to approach the target/obstacle (during interval between the appearance of the stimulus and the target/obstacle step), (iii) stepping accuracy for target conditions (distance between the centre of the target and the centre of the foot) and for the obstacle condition (the smallest distance between the edge of the foot and the edge of the obstacle), and (iv) step length, step velocity and the percentage of the gait cycle spent in double support (double-support time) during baseline (average of 4th and 5th steps) and experimental conditions (for target/obstacle and previous steps). An electronic walkway (GAITRite® mat, v4.0, 2010 CIR Systems, USA) recorded the temporal and spatial gait parameters. Position coordinates of the foot and target/obstacle obtained from the electronic walkway were used to determine incorrect responses and to calculate stepping accuracy.

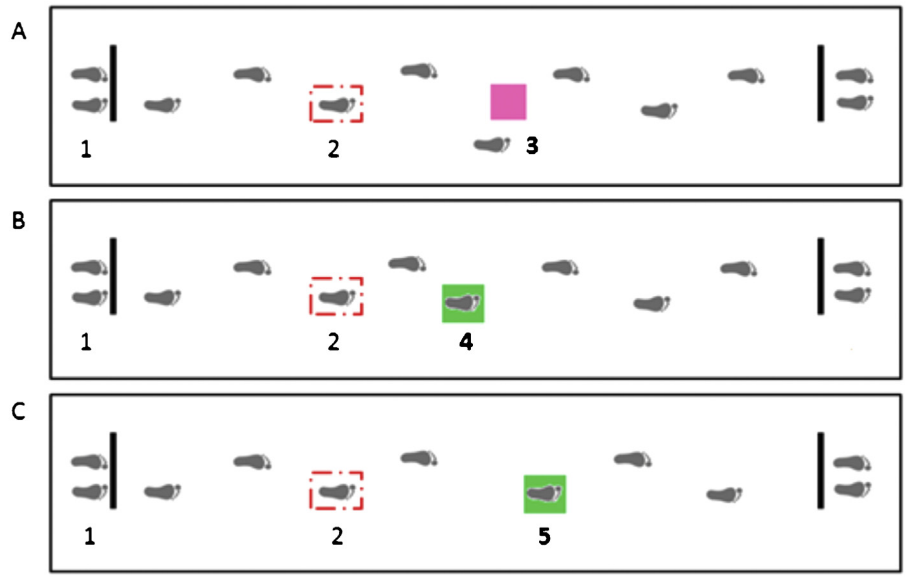

Fig. 1. Overhead view of the experimental setup including obstacle avoidance (A), short target (B) and long target (C) conditions. The starting position (1) was adjusted to align the obstacle (3) with the fifth foot landing location based on the average foot placement from the baseline walking trials. The stepping targets were projected in two locations – 245 mm anterior (4) and 245 mm posterior (5) to the obstacle position (centre to centre distance), and thus required a short or a long step length respectively. The projection system for the three stimulus consisted of three torches installed in the ceiling and connected to a control box. A force sensitive resistor (Sparkfun SEN-09376) placed underneath the participant's right shoe and connected to a wireless transmitter attached to the participant's ankle triggered the light projection on the third heel strike following gait initiation (2).

2.4. Statistical analysis

For variables with right skewed distributions, data were $\log_{10}$ transformed. Differences in neuropsychological and physiological function between young and old groups were assessed using independent sample *t*-tests. Between-groups differences in incorrect responses in the gait adaptability test were examined using Chi-square tests and differences in number of steps and stepping accuracy for each target/obstacle condition were examined using respectively, Mann Whitney-U test and *t*-tests.

For each stimulus condition (obstacle, short target and long target), repeated measure analysis of variance (ANOVA) tests were used to evaluate the effects of age and stepping condition (baseline, walk-through, previous and target/obstacle steps) on step length and step velocity. Differences in double-support time were considered per stride and thus the ANOVAs evaluated the effects of age and stepping condition (baseline, walk-through and target/obstacle strides). Pairwise comparison post hoc tests were performed on main effects of condition and interactions found to be significant. Trials in which participants made a mistake were excluded from these analyses. The statistical analyses were performed using SPSS (Version 22 for Windows, SPSS Science, Chicago, USA). All significance levels were set at $p < 0.05$ and Bonferroni adjusted for multiple comparisons.

3. Results

No significant anthropometric differences were found between the young and older participants (Table 1), so gait measures were not normalised to stature in the between-group comparisons.

3.1. Incorrect responses, stepping accuracy and number of steps taken

Eleven older adults (22%) made at least one mistake in the gait adaptability test while none of the younger participants made any mistakes ($\chi^2 = 5.467$, $p < 0.02$).

Table 2 presents young and older participants' stepping accuracy and number of steps for each stimulus condition. Compared with young adults, older adults had poorer stepping accuracy in the short target condition and took more steps while approaching the obstacle and both short and long targets. Fig. 2 presents typical walking performance of a younger and an older adult for each condition. Independent *t*-tests analyses within the older sample revealed that the duration between trigger onset and target/obstacle step was significantly longer in the trials where participants took more than two steps in this time interval vs. two steps only (short target: 1.63 s vs. 1.12 s, $t_{137} = 11.247$, $p < 0.001$; long target: 1.80 s vs. 1.24 s, $t_{142} = 11.048$, $p < 0.001$; obstacle avoidance: 1.84 s vs. 1.21 s, $t_{139} = 13.101$, $p < 0.001$).

3.2. Spatiotemporal variables

Table 3 presents young and older participants' spatiotemporal variables for each condition.

Post hoc within-group effects indicated that young individuals maintained the same walking pattern for both the baseline and walk-through conditions, whereas older participants reduced their step length and step velocity and increased their double-support time significantly in the walk-through condition. Post hoc between-group effects revealed that compared with the younger group, the older group had a significantly shorter step length in baseline and walk-through conditions, as well as slower step velocity and increased double-support time in the walk-through condition.

3.2.1. Short target condition

ANOVAs between baseline, walk-through and short target conditions revealed significant group*condition interactions for step length ($F_{3,204} = 8.588$, $p < 0.001$), step velocity ($F_{3,204} = 4.950$, $p < 0.003$) and double-support time ($F_{2,136} = 6.189$, $p < 0.004$). Post hoc tests of within-group comparisons indicated that both young and older participants reduced length and velocity of the previous and target steps compared with baseline and

Table 2
Mean ± SD stepping accuracy and number of steps for the young and older groups on short target, long target and obstacle avoidance conditions.

Variables	Short target			Long target			Obstacle avoidance		
	Young	Old		Young	Old		Young	Old	
Stepping accuracy (cm)	4.4 ± 2.9	5.8 ± 3.0[a]	t_{69} = −2.466	4.5 ± 1.7	6.1 ± 3.4	t_{69} = −1.552	10.0 ± 5.0	9.10 ± 3.9	t_{69} = .799
Number of steps	2.0 ± 0.7	2.2 ± 0.4[a]	Z = −2.203	2.3 ± 0.4	2.9 ± 0.6[a]	Z = −4.155	2.1 ± 0.2	2.7 ± 0.6[a]	Z = −3.981

[a] Significantly different from the younger group within condition ($p < 0.05$).

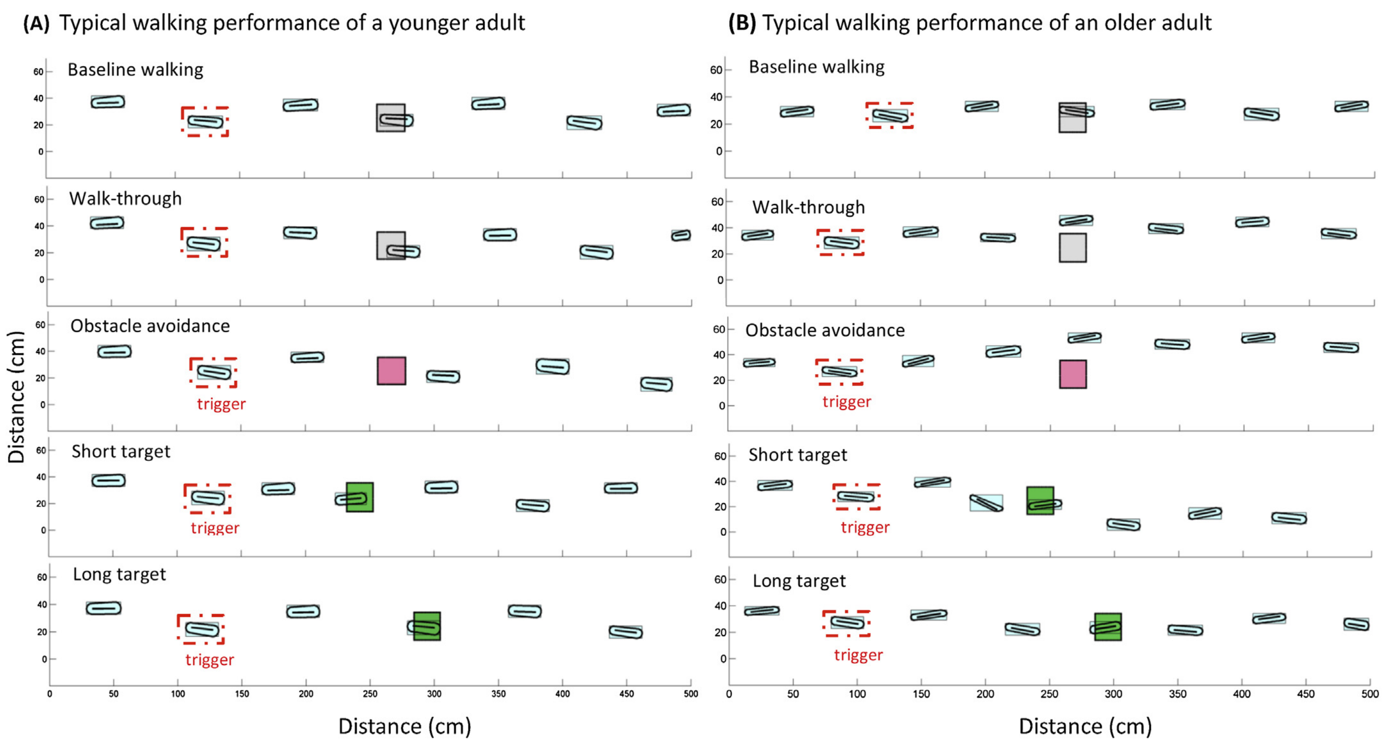

Fig. 2. Typical walking performance of a younger adult (A) and an older adult (B) for each condition (baseline, walk-through, obstacle avoidance, short target and long target). Position coordinates of the foot and target/obstacle were obtained from the electronic walkway and were plotted using a Matlab routine. Note: Only the footfalls recorded by the electronic walkway are shown. Obstacle position is showed in the baseline and walk-through conditions as a representation of its location. No stimulus was triggered for those conditions. The target/obstacle appearance was triggered on the heel strike of the footfall indicated by the dashed red boxes. (A)Typical walking performance of a younger adult, (B) Typical walking performance of an older adult.

walk-through conditions. Both groups also increased the time spent in double-support in the short target compared with the baseline condition, and this increase was also significant against the walk-through condition in the young group. Post hoc between-group effects revealed that compared with the young, the older participants displayed a reduced length and velocity of the previous step, and increased double-support time on the target stride.

3.2.2. *Long target condition*

ANOVAs between baseline, walk-through and long target conditions revealed significant group*condition interactions for step length ($F_{3,204}$ = 7.091, $p < 0.001$), step velocity ($F_{3,204}$ = 9.446, $p < 0.001$) and double-support time ($F_{2,136}$ = 13.747, $p < 0.001$). Post hoc tests of within-group comparisons indicated that the target step was longer and faster than the previous step in both young and older groups. However, compared with the baseline condition, the older participants reduced length and velocity of the previous and target steps while the young participants only reduced velocity of the previous step. Older but not young adults also spent more time in double-support in the long target compared to the baseline condition. Compared with the walk-through condition, older participants reduced length and velocity of the previous step. Post hoc between-group effects revealed that compared with young, older adults had reduced step lengths and velocity of the previous and target steps as well as increased double-support time on the target stride.

3.2.3. *Obstacle avoidance condition*

The percentage of participants who adopted a long step strategy (young 38% vs. old 28%) or a side step strategy (young 33% vs. old 24%) to negotiate the obstacle did not differ between groups. The remaining percentage of people (young 29% and old 48%) alternated between both strategies.

ANOVAs between baseline, walk-through and obstacle avoidance conditions revealed significant group*condition interactions for step length ($F_{3,204}$ = 5.984, $p < 0.002$), step velocity ($F_{3,204}$ = 10.358, $p < 0.001$) and double-support time ($F_{2,136}$ = 9.807, $p < 0.001$). Post hoc tests within-group effects indicated that the obstacle step was longer and faster than the previous step in both groups. Compared to the baseline condition, older participants reduced step length and velocity of the previous step as well as the obstacle step velocity, while young participants reduced velocity of the previous step and increased step length of the obstacle step. Older but not young adults

Table 3
Mean ± SD step length, step velocity and double support time for the participants on baseline, walk-through, short target, long target and obstacle avoidance conditions.

Variables	Baseline	Walk-through	Short target		Long target		Obstacle avoidance	
			Previous step	Target step	Previous step	Target step	Previous step	Obstacle step
Step length (cm)								
Younger	72.2 ± 6.0	72.5 ± 6.7	64.8 ± 6.4[b,c]	53.7 ± 9.6[b,c,d]	71.7 ± 7.0	77.4 ± 13.4[d]	71.3 ± 7.5	78.0 ± 13.1[b,c,d]
Older	66.1 ± 9.1[a]	62.5 ± 9.3[a,b]	54.2 ± 13.8[a,b,c]	54.2 ± 11.9[b,c]	54.6 ± 11.9[a,b,c]	62.3 ± 16.8[a,b,d]	55.5 ± 13.5[a,b,c]	66.3 ± 13.9[a,d]
Step velocity (m/s)								
Younger	1.32 ± 0.2	1.27 ± 0.2	1.17 ± 0.2[b,c]	1.09 ± 0.2[b,c]	1.24 ± 0.2[b]	1.32 ± 0.2[d]	1.24 ± 0.2[b]	1.32 ± 0.2[d]
Older	1.24 ± 0.2	1.10 ± 0.2[a,b]	0.97 ± 0.3[a,b,c]	1.00 ± 0.2[b,c]	0.99 ± 0.2[a,b,c]	1.07 ± 0.3[a,b,d]	0.98 ± 0.2[a,b,c]	1.09 ± 0.3[a,b,d]
Double support (%)								
Younger	27.3 ± 3.5	27.5 ± 3.0	28.9 ± 2.8[b,c]	26.6 ± 2.5	26.3 ± 3.2[c]			
Older	28.6 ± 3.3	31.0 ± 3.4[a,b]	31.4 ± 4.0[a,b]	31.4 ± 3.6[a,b]	30.0 ± 4.0[a,b,c]			

[a] Significantly different from the younger group within condition ($p < 0.05$).
[b] Significantly different from the baseline condition within group ($p < 0.05$).
[c] Significantly different from the walk-through condition within group ($p < 0.05$).
[d] Significantly different from the previous step within group ($p < 0.05$).

also spent more time in double-support in the obstacle condition compared with the baseline condition. Compared with the walk-through condition, older adults reduced length and velocity of the previous step and increased double-support time, while younger adults increased the obstacle step length and reduced double-support time on the obstacle stride. Post hoc between-group effects revealed that compared with the young group, older adults showed reduced step lengths and velocity of the previous and obstacle steps as well as increased double-support time on the obstacle stride.

4. Discussion

This study describes a new gait adaptability test in which participants had to either avoid an obstacle or step onto a target presented at two steps ahead of the individual while walking; a paradigm that required a disruption of gait rhythm by an adaptation of foot landing location. Our hypotheses were supported by the significant age group differences in the gait adaptability performance.

4.1. Incorrect responses, stepping accuracy and number of steps taken

Our findings that mistakes were more prevalent in the older group are in line with previous findings of increased failure rates to avoid unpredictable obstacles in older people [3,5,6,18]. This could be due to age-related declines in sensorimotor and cognitive functions, as previous studies have reported that sensorimotor determinants of obstacle contacts in healthy older adults include reduced lower limb strength [19] and poor depth perception [20]. Moreover, increased obstacle avoidance failure rates were evident under dual-task conditions [21] and were also associated with impairments in executive functioning (attention, response inhibition, problem solving) [22].

Consistent with previous study findings [7,8,23,24], the older adults showed reduced stepping accuracy in the short target condition. There is evidence showing that compared with young, older adults need additional visual information about a target (i.e. earlier and longer fixation periods) for accurate stepping [23,24] and have slower reaction times for initiating eye movements towards stepping targets [8,24]. Hence, the short available response distance of the short target condition may have contributed to the poorer stepping accuracy of the older adults in this study. Limited executive function [7] and/or less effective balance control [25] may also have contributed to the poorer stepping accuracy. Furthermore, the long available response distance of the long target condition may have allowed older participants a more timely use of visual information about the target and, who, thus, had similar stepping accuracy to the young group. Also, no age-difference for stepping accuracy in the obstacle condition was identified. The obstacle avoidance task may not have been challenging enough to elicit a group difference.

The increased number of steps taken by the older adults to approach the target/obstacle is also consistent with previous study [26]. This multiple step strategy may have been adopted to compensate for motor deficits [27] and/or slowed cognitive processing [28], or indicates a difficulty in increasing step length to hit or avoid the targets, as reported in other settings, such as unpredictable stepping-target shifts on treadmill walking [29]. The multiple step strategy may also have constituted a way of gaining additional time to process the conflict resolution task (step or avoid the stimulus).

4.2. Spatiotemporal variables

The older adults adopted a conservative gait pattern throughout the experiment, i.e. even when a target/obstacle was not presented (walk-through condition). This is consistent with previous research that has shown people adopt a secure walking pattern after forewarning of a possible trip [15] or obstacle appearance [17]. In our gait adaptability test, participants knew that the target/obstacle might appear in some trials. Thus, the walk-through condition was more cognitively demanding than the baseline walking condition which may explain the more conservative walking pattern adopted by the older adults. Although older adults adapted their gait due to the expectation of a target/obstacle appearance, further gait adjustments were detected for each target/obstacle condition. These findings demonstrate that older adults are more affected by the possibility of a hazard appearing on the pathway and that the target/obstacle conditions offered sufficient perturbation requiring further gait adjustments. These findings also suggest older adults have a limited capacity to cope with complex walking tasks requiring increased cognitive demands, as reported in previous studies investigating the influence of secondary tasks on obstacle avoidance performance [6,18,20,21].

In the short target condition, young and older adults adapted their gait parameters similarly by reducing length and velocity of the previous and target steps and increasing double-support time. The observed gait adjustments are in line with the requirements of the task, showing that the short target represented a perturbation to the participants' gait pattern. Specifically, the changes seen in the previous step and double-support time were more pronounced among the older adults, showing that they were more affected by the short target at an earlier stage. Age-related declines in both physical [1] and cognitive functioning [28] may explain the more pronounced gait adaptations towards the short target.

When negotiating the long target, older adults adjusted their gait parameters more than the young group did. While the older adults reduced length and velocity of both the previous and target steps and increased the time spent in double-support, young adults only reduced the velocity of the previous step and tended to increase target step length. Similarly, to avoid the obstacle, young adults reduced the velocity of the previous step and lengthened the obstacle step. The obstacle step was also faster than the previous step. In contrast, the older adults shortened the previous step, reduced velocity of both previous and obstacle steps and increased the time spent in double-support. Gait adaptations seen in the young group likely represent the expected behaviour to deal with the long target and avoid the obstacle. The reduced step length adopted by the older adults corroborates with the increased number of steps taken to approach the target. This more conservative, less efficient strategy is consistent with previous findings of poorer gait adaptability performance of older people in challenging conditions [3,23,27]. Again, age-related declines in both physical [1] and cognitive functioning [28] may explain the more conservative gait adaptation.

Additionally, similar proportions of younger and older participants stepped to the side, rather than over the obstacle and the majority of the older adults alternated between both strategies. This suggests that the side and long step strategy may be equally efficient in our particular experimental protocol. Minimal displacement of the foot-landing location is an important factor for selecting alternate foot placement [30]. Possibly, the size of the obstacle influenced the choice of a step strategy. The length and width of our obstacle was equal (square shape) and the obstacle was not too long or too wide (approximately a third of step length) to favour either strategy.

4.3. Strengths and limitations

The strengths of our study include the novelty of the test paradigm that combined precision steps and obstacle avoidance in an over-ground walking task and the large sample sizes for an experimental study of this type. Importantly, the inclusion of four randomised stepping conditions (walk-through, short target, long target and obstacle avoidance) may have been necessary to reveal the age differences identified. We also acknowledge the study has certain limitations. The older sample comprised healthy community-living people, so the findings would not generalise to frailer older people at high risk of falls. Further studies aimed at identifying sensorimotor and cognitive correlates, the effects of secondary tasks, brain activity as assessed with mobile functional imaging such as functional near infra-red spectroscopy and faller–non-faller differences could provide further insights into gait adaptability performance with this test paradigm.

4.4. Conclusion

In conclusion, we found that compared with their younger counterparts, the older adults exhibited a more conservative gait adaptability strategy characterised by slow, short and multiple steps as well as longer time in double-support. Even so, the older adults demonstrated a poorer stepping accuracy and made more mistakes in the test. This reduced gait adaptability may place older adults at an increased risk of falling when negotiating unexpected hazards. Strategies for improving gait adaptability may assist the efficacy of fall prevention programmes.

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Conflict of interest

The authors declare no conflicts of interest.

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