

# The Association between Age-Related Cognitive Changes and Obstacle Avoidance: Focusing on Memory-Guided Limb Movements

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## Research Article

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# Abstract

An association between cognitive impairment and tripping over obstacles during locomotion in older adults has been suggested. However, owing to its memory-guided movement, whether this is more pronounced in the trailing limb is poorly known. We examined the age-related changes in stepping-over, focusing on trailing limb movements, and their association with cognitive performance. Age-related change in obstacle avoidance was examined by comparing the foot kinematics of 105 older and 103 younger adults when stepping over an obstacle. The difference in clearance between the leading limb and trailing limb ( $\Delta$  clearance) was calculated to determine the degree of decrement in the clearance of the trailing limb. A cognitive test battery was used to evaluate cognitive function among older adults for assessing their association with  $\Delta$  clearance. Older adults showed a significantly lower clearance of the trailing limb than younger adults, resulting in a greater  $\Delta$  clearance. The significant correlations between greater  $\Delta$  clearance and scores of Montreal Cognitive Assessment and delayed recall of the Wechsler Memory Scale-Revised Logical Memory. Our results suggest that memory functions may contribute to the control of trailing limb movements, which can secure a safety margin to avoid stumbling on an obstacle, during obstacle avoidance locomotion.

## Introduction

Motor and sensory systems are linked by higher-order neurological processes and cognition, which are required for planning movements and for responding to changes within the environment<sup>1,2</sup>. Recent studies have demonstrated that cognition plays an important role in the regulation of locomotion in older adults<sup>1,3-5</sup>. Thus, it has been suggested that cognitive impairment is related to an increased risk of falls<sup>1,6</sup>.

Tripping while stepping-over an obstacle is one of the most important problems leading to falls, and it could be affected by cognitive impairment<sup>7,8</sup>. Indeed, patients with Alzheimer's disease (AD) have a higher frequency of contact with obstacles than healthy older adults<sup>9</sup>, and such contact seems to be more frequent in the trailing limb<sup>10</sup>. This may be because stepping over an obstacle with the trailing limb is mostly guided by the working memory of the obstacle height<sup>10-13</sup>. This concept has been also confirmed in studies using quadrupedal animals, which cannot visually recognize their hindlimbs movements, where AD model mice showed a higher frequency of contact of the hindlimbs during an obstacle avoidance task than non-AD model mice<sup>14</sup>. Hence, cognitive impairment including age-related memory decline may contribute to a failed trailing limb movement during stepping-over action as indicated by the significantly lower foot clearance than that of the leading limb<sup>15</sup>.

Although the effects of age-related cognitive decline on the human trailing limb movements during obstacle avoidance are not well-known, relevant studies suggested the possibility of such age-related changes decreasing foot clearance of the trailing limb. For instance, in a previous study with participants stepping over an obstacle with lower height (10 % of participants' leg length), older adults showed slightly

lower foot clearance of the trailing limb compared with young adults whereas that of the leading limb did not change with age<sup>16</sup>. This resulted in foot clearance asymmetry, which suggests that trailing limb movement may be affected by aging. Furthermore, older adults who were at a higher risk for falls, which was detected by fall history and a decline in the lower extremity, showed lower trailing limb clearance and thus greater foot clearance asymmetries than the low-risk older and young adults<sup>17</sup>. While in this previous study high-risk older adults showed impairments of the lower extremity, they also showed a decline in cognitive function, suggesting that poor trailing limb movement could be resulting from lower cognitive performance.

Assuming that cognitive impairment affects foot clearance during obstacle avoidance, it may also suggest an influence on lower limbs behavior during obstacle avoidance, including toe-obstacle distance and heel-obstacle distance. This is supported by a previous study that showed that patients with AD land their leading foot significantly closer to the obstacle than older controls<sup>9</sup>. Although studies suggest that age-related cognitive decline may affect the control of foot-obstacle distance for obstacle avoidance, particularly the trailing limb, no study to date have determined the cognitive correlates of impaired trailing limb control during obstacle avoidance in older adults.

Another factor to consider is the variability in each obstacle avoidance parameter (i.e., foot clearance, toe-obstacle distance and heel-obstacle distance), which may be more related to cognitive functioning than absolute values. Particularly spatial variability is a measure of healthy cognitive control because it expresses corrective adjustments over lower limbs movements<sup>18,19</sup>. Although the association between cognitive impairment and greater gait variability during obstacle negotiation has been suggested<sup>20-22</sup>, there have been few reports about their association during stepping-over action.

In the present study, we determine whether age-related change in limb movements during obstacle avoidance arise from lower cognitive performance among older adults, focusing on trailing limb movement. To this end, (1) having foot clearance as the main endpoint, comparisons were made between that of the leading and trailing limbs for young and older adults to determine an age-related decline in obstacle avoidance. Then, (2) the difference between these foot clearances (i.e., foot clearance asymmetry) was calculated to reveal the cognitive correlates of the impaired control of the trailing limb. In addition, (3) we also examined age-related differences in parameters of the stepping-over action and their correlation with cognitive performance. We hypothesize a worsening in the control of the trailing limb indicated by decreased foot clearance of the trailing limb compared to that of the leading limb and greater trial-to-trial variability of parameters of the stepping-over action will be observed among older adults, and its decrement would be associated with worse cognitive functioning, particularly memory decline. The findings of the present study can shed light on the role of cognition on lower limb control during obstacle avoidance and may help to prevent tripping over an obstacle, which results in falls among older adults.

## Results

As a result of the obstacle avoidance task, four older adults and four young adults were excluded from the analysis because their data could not be parsed (e.g., missing due to technical issues). Thus, 103 young and 105 older adults were included in the present analyses. Table 1 shows the participants' characteristics. Almost one-third of our older participants (29.0 %) were young-older adults (<75 years old). They had normal global cognitive function (mean MMSE = 28.5), and good mobility (mean usual gait speed = 1.36 m/s) for their age.

### ***Aging effects on obstacle avoidance parameters***

Figure 2 A shows the results of the leading and trailing limb clearances for young and older adults. The repeated-ANOVA revealed no significant effects for the limb ( $F_{1,204} = 1.2, p = 0.27, \text{partial } \eta^2 = 0.01$ ) or age group ( $F_{1,204} = 0.7, p = 0.38, \text{partial } \eta^2 = 0.002$ ) factors; but the significant interaction between the two factors was observed ( $F_{1,204} = 8.6, p < 0.01, \text{partial } \eta^2 = 0.03$ ). The results of post-hoc analyses confirmed that there were significant differences in clearance between the leading limb and trailing limb among older adults ( $p < 0.01$ ), and in the clearance of the trailing limb between the young and older adults ( $p = 0.04$ ); older adults showed significant low clearance in their trailing limb compared to that of their leading limb and the trailing limb of young adults.

Table 2 shows the differences in other parameters of obstacle avoidance between young and older adults. ANCOVA revealed that the toe-obstacle distance among older adults was significantly larger than that of young adults ( $F_{1,204} = 11.2, p < 0.01, \text{partial } \eta^2 = 0.05$ ), and the heel-obstacle distance among older adults was significantly smaller than that of young adults ( $F_{1,204} = 99.5, p < 0.01, \text{partial } \eta^2 = 0.33$ ). Furthermore, a greater variability in the heel-obstacle distance, compared to young adults, was observed in older adults ( $F_{1,204} = 21.9, p < 0.01, \text{partial } \eta^2 = 0.10$ ). There were no significant age-related-differences in variabilities in the toe-obstacle distance, leading foot clearance, and trailing foot clearance.

### ***The association of age-related cognitive changes with obstacle avoidance***

Figure 3 shows the significant correlations between  $\Delta$  clearance and the measurements of cognitive function among older adults. Partial correlation analyses adjusting for gender, age, the length of the lower limb, and gait speed showed that scores of the MoCA and LM immediate-recall were negatively correlated with  $\Delta$  clearance, indicating that older adults who had lower cognitive scores showed a greater gap between leading and trailing limbs clearances (i.e., lower clearance of trailing limb). On the other hand, TMT-A ( $r = 0.08, p = 0.44$ ), TMT-B ( $r = 0.17, p = 0.18$ ), and LM delayed-recall ( $r = 0.23, p = 0.02$ ) did not correlate with  $\Delta$  clearance.

Partial correlation analyses adjusting for the aforementioned covariates, which were performed on the basis of all resultant age-related significant differences between young and older adults, showed no

significant correlations among the toe-obstacle distance, heel-obstacle distance, variability in the heel-obstacle distance, and cognitive variables (Table 3).

Typical toe trajectories in stepping-over an obstacle among young adults, older adults without significant cognitive impairments (MMSE = 30; MoCA = 30; LM immediate recall = 26; and LM delayed recall = 23), and older adults with significant cognitive impairment (MMSE = 27; MoCA = 18; LM immediate recall = 14; and LM delayed recall = 9), are illustrated in Figure 4. Supporting the aforementioned results, the toe trajectory among older adults with significant cognitive impairments showed a low clearance of the trailing limb compared to cognitively healthy controls (young and older adults without cognitive impairment) whereas no difference was found in the heel-obstacle distance between older adults with and without cognitive impairments.

## Discussion

We wished to ascertain whether age-related cognitive declines resulted in low obstacle clearance of the trailing limb since its movement regulation was considered to be memory-guided. In this study, we found a significant lower clearance of the trailing limb of older adults than that of the younger adults and memory-related change in foot clearance of the trailing limb among older adults, which is consistent with our hypothesis. The results lend support to previous findings indicating that rather than being an automated task, obstacle avoidance relies on memory alongside vision, due to its invisible movement. However, although we also hypothesize that increased trial-to-trial variability in the stepping-over action would be associated with worse cognitive functioning, we did not confirm this despite the observed age-related increment in variabilities in the heel-obstacle distance.

In the present study, older adults showed a significantly lower clearance of the trailing limb compared to that of young adults but not the case of the leading limb, thus resulting in a greater difference between the clearances of the leading and trailing limbs among older adults. This was evident in those who had lower cognitive performance in terms of memory and global cognition detected by LM and MoCA. Scores of LM immediate and delayed recalls reflect the ability of short- and long-term episodic memory, and they are associated with the ability of the working memory<sup>23</sup>. It has been implied from earlier studies of humans that memory functions are involved in the control of limb movements during obstacle avoidance locomotion<sup>21,24</sup>, as well as quadrupeds. For instance, accurate stepping movements of the trailing limb based on obstacle memory can be performed after a delay period of 2 minutes<sup>25</sup>. Low clearance of the trailing limb is observed in older adults whose impaired memory function is therefore assumed to be diminishing their ability to internally represent an obstacle encountered during walking<sup>11</sup>, supporting the concept that the memory of an obstacle encountered during walking would persist during obstacle avoidance<sup>11-13,25</sup>.

The MoCA was correlated with  $\Delta$  clearance in the present study. The MoCA covers important cognitive domains such as memory, executive functions, visuospatial abilities, language, attention, concentration, and temporal and spatial orientation; and has thus been used as a screening test for mild cognitive

impairment<sup>26</sup>. Additional analysis (not shown in the Results section) that examined correlations with the MoCA's cognitive domains showed that memory significantly associated with  $\Delta$  clearance ( $r = 0.22$ ,  $p = 0.03$ ). The correlation between the MoCA and greater foot clearance asymmetries caused by a low clearance of the trailing limb may be attributed mainly to memory decline, although it is undeniable that impairments in a wide range of cognitive functions may also be involved in the persistent internal representation of an obstacle during obstacle avoidance.

Possible brain regions responsible for persistent memory regarding an obstacle for controlling invisible limb movements during obstacle avoidance have been suggested in previous studies, and area 5 of the posterior parietal cortex (PPC) appears to be involved in this memory-guided movement<sup>27-29</sup>. McVea et al., have proposed a conceptual model for memory-guided invisible limb movements stating that an efference copy signal related to motor commands producing a stepping action in the leading limb (foreleg in the case of animals) initiates activity in the neurons in area 5, leading to the maintenance of the memory of the obstacle height<sup>29</sup>. This concept has been supported by findings that area 5 of the PPC deactivation, including lesions, resulted in the impairment of the ability of cats to maintain the height of an obstacle in their working memory and reduced clearance for both the leading and trailing hindleg steps<sup>28,29</sup>. Additionally, a significantly decreased perfusion in the PPC is observed among older adults with MCI who generally show lower scores in the MoCA and logical memory, compared to that of cognitively healthy older adults<sup>30</sup>. Our results show that cognitive impairment-related lower clearance of the trailing limb could be attributed to functional impairment of the PPC.

Although older adults were likely to place their trailing foot further from the obstacle before stepping-over and landed their leading foot closer to the obstacle after having crossed it, these age-related changes were not correlated with cognitive function. This is partly consistent with the previous finding that AD patients who showed greater impairments in cognitive function tend to land more closely to the obstacle after crossing it<sup>9</sup>, suggesting an increased risk of tripping on or collision with an obstacle. A possible interpretation of the discrepancy between the previous findings and those from the present study is that the foot placing just before and after stepping-over an obstacle is mainly affected by impairments in the ability to control gait and posture, such as the neuromuscular system, rather than cognition; this holds true for the variability in the heel-obstacle distance among older adults, which was significantly different from that of young adults since it was not associated with cognitive impairments.

Typical toe trajectories during stepping-over (Fig 4), clearly showed the low clearance of the trailing limb in older adults with cognitive impairments being consistent with results that older adults who had lower cognitive scores showed a greater gap between leading and trailing limb clearances (i.e., lower clearance of trailing limb). It is possible that the low clearance of the trailing limb, which was also observed in the example of the toe trajectory, could be attributed to a change in the toe trajectory due to placing their trail foot further from the front of the obstacle, thus resulting in them landing close to the obstacle with their leading heel. However, this assumption is ruled out because low and insignificant correlation coefficients among toe-obstacle distance, heel-obstacle distance, and clearance of the trailing limb were observed in

both young and older adults (data was not shown). Also considering that the toe-obstacle distance and heel-obstacle distance were not associated with cognitive function, cognitive impairment-related low clearance of the trailing limb may be independent of these behavioral changes before and after stepping-over.

Our results demonstrated neither a significant difference in foot clearance variabilities between young and older adults nor a significant association between poor cognitive function and greater variabilities in foot clearances. This is consistent with a prior finding that AD patients did not show a significantly greater foot clearance variability in both the leading and trailing foot, as compared with healthy controls, whereas increased gait variability during the approach phase was observed<sup>20</sup>. It is therefore believed that cognitive impairments may attenuate the anticipatory gait adjustments during obstacle avoidance, resulting in a greater gait variability when approaching an obstacle<sup>21</sup>, but no foot clearance during stepping-over. Further studies will be required to confirm our results in other experimental settings, such as having a longer approach distance to an obstacle.

The strength of this study is that it is the first to show age-related lower clearance of the trailing limb of older adults and its association with poor cognitive function with a relatively large sample. However, there are limitations that need to be considered when interpreting the results. The cross-sectional design of this study precludes us from exploring the causal relationship between the associations found. Although the present study used six cognitive assessments to capture participants' cognitive profile, if we had measured other functional domains of cognition, it may have reinforced our findings regarding the association between a low clearance of the trailing limb and lower cognitive performance, particularly in memory. Our results were controlled for potential confounders; however, residual confounding covariates may still be present.

In conclusion, our results showed that a low clearance of the trailing limb was observed in older adults and was evident in those with lower cognitive performance. The findings of this study suggest that memory functions contribute to the control of limb movements, which can secure a safety margin to avoid stumbling on an obstacle, during obstacle avoidance locomotion.

## Methods

### *Participants*

Older participants were volunteers recruited from a database of community-dwelling older adults available at the Tokyo Metropolitan Institute of Gerontology (TMIG). Participants were included in the study based on the following criteria: 1) being able to walk independently for 5 minutes; 2) being fully functional in instrumental activities of daily living (IADL) assessed using the TMIG Index of Competence, which is a questionnaire comprising three multidimensional subscales: the IADL, intellectual activity, and social function<sup>31</sup>; and 3) being able to complete both obstacle avoidance tasks and cognitive assessments. The exclusion criteria included having 1) Parkinsonism or any other neurological disorder

(e.g., severe stroke) with a residual motor deficit, 2) active osteoarthritis affecting lower limbs performance, and 3) dementia, which was determined by self-reported medical history and medical interview conducted by a specialist, or significant cognitive impairment detected by the cut-off of 24 points on the Mini-Mental State Exam (MMSE)<sup>32</sup>, which has a maximum score of 30 points, with higher scores indicating higher overall cognitive function. We also confirmed that none of the participants wore multifocal glasses that might cause misperception for an object. Younger participants were also recruited from several universities as controls. We confirmed they had no physical, neurological, or mental disorders, and used no medication. In total, 109 older adults aged  $78.1 \pm 5.6$  years, and 107 young adults aged  $27.0 \pm 5.8$  years, participated in the study.

Ethical approval was obtained from the Tokyo Metropolitan Institute of Gerontology Ethics Board, and participants signed an informed consent form obtained at the time of enrolment. The study was conducted in accordance with the Declaration of Helsinki.

## ***Measurements***

Data on participants' health conditions were collected through interviews before the obstacle avoidance task and cognitive assessments. The interview items included demographics, comorbidities, history of hospitalization, and medication. The order of obstacle avoidance task trials and cognitive assessments were both conducted in random order to prevent a potential order affect in motor and cognitive performance.

### *Obstacle avoidance task*

#### *Experimental setup and apparatus*

The experiment was conducted in a sound-isolated flat room, illuminated with a homogeneous white light. An obstacle made of expanded polystyrene measuring 150 mm by 600 mm by 10 mm (height by width by depth), with L-brackets was attached to the bottom to hold the obstacle upright.

Foot kinematics data were collected using a three-dimensional motion capture system (OptiTrack V120: Trio, NaturalPoint, Inc.), which was located diagonally on the right side in front of a participant, at a sampling frequency of 120 Hz. Reflective markers (9.5 mm diameter) were attached directly on the flat walking shoes prepared by the experimenter to estimate the toe and heel position: first and fifth toes, and center of heel on both sides of the feet. Markers were also placed on the upper front edge of the obstacle to determine its location and height within the motion capture system. Data was corrected using Motive software (NaturalPoint, Inc.) and analyzed using Matlab (Mathworks, Sherborn, Massachusetts, USA). Time series data of each marker were smoothed by a second-order Butterworth low-pass filter with a 10 Hz cutoff frequency.

## *Procedure*

The obstacle was placed 150 cm away from the participant. Then, on a verbal command of "go," participants walked down the pathway at a self-selected pace and stepped-over the obstacle with four steps. In this case, participants were instructed to start walking from their left foot, take (walk) three steps, and place the next step over the obstacle from the right foot, as the fourth step (i.e., left foot was the trailing foot), and keep walking until they reached the end line. No time restriction was imposed on their performance. Several practice trials were conducted before the main trials until their stepping-over action become stable. After the practice trials, the participants were allowed to amend their starting position, with regard to distance, back and forth to adjust their steps for smooth stepping-over action. They performed four consecutive times.

We measured the following variables as parameters of the stepping-over action (Figure 1): (a) leading foot clearance, which is the vertical distance between the toe-tips detected by reflective markers attached on first and little fifth toes, of the leading-limb (first limb to pass over the obstacle) and the upper edge of the obstacle as each respective marker passed over the obstacle; (b) trailing foot clearance, which is the vertical distance between the toe-tips of the trailing-limb (the second limb to pass over the obstacle) and the top of the obstacle as it passed over the obstacle; (c) toe-obstacle distance, which is the horizontal distance between the trailing-limb toe tip and the obstacle right before stepping-over an obstacle; (d) heel-obstacle distance, the horizontal distance between the heel-tip of the leading-limb and the obstacle for the foot placement right after crossing the obstacle. Each mean variable and each variability (Coefficient of Variation, CoV, %) for the four trials were calculated.

## *Cognitive assessments*

To better understand the cognitive influence on obstacle avoidance, cognitive domains namely global cognition, executive function, and memory were evaluated using the Montreal Cognitive Assessment (MoCA), the Trail Making Test (TMT)-A,-B, and the logical memory subtest of the Wechsler Memory Scale (LM), respectively. Clinical psychologists carried out these tests.

The MoCA, comprises six domains examining overall cognitive function: (i) time and place orientation; (ii) memory; (iii) visuospatial abilities; (iv) executive function; (v) attention and working memory; and (vi) language, and having a maximum score of 30-points, with higher scores indicating higher overall cognitive function<sup>26</sup>.

The TMT-A assesses simple visual search and motor speed skills<sup>33</sup>. Participants are asked to draw a line with a pencil to connect 25-printed numerals from 1 to 25 in ascending order. In the TMT-B, to test higher-order cognitive skills such as working memory and mental flexibility<sup>33</sup>, participants perform a visual-

motor task similar to the TMT-A, except this includes connecting 13-numerical numbers and 12-Japanese hiragana characters while alternating numbers and letters in ascending order. Shorter required time for these tests indicates higher executive function.

For LM, which can comprehensively assess memory, participants were orally presented two short stories separately, and were then asked to recall each story verbatim (immediate recall)<sup>34</sup>. The maximum score for each story recall is 25-points (i.e., a total of 50-points). Approximately 30-minutes after immediate recall, a free recall of the story is again elicited (delayed recall). Delayed recall tasks have the same scores (total being 50 points).

### *Covariates*

Gender and the length of the lower limb (i.e., distance from the greater trochanter to the ground through the lateral malleolus) were adopted as covariates when examining the age-related differences in parameters of obstacle avoidance. In the case of examining the association of parameters of obstacle avoidance with cognition, gender, age, the length of the lower limb, and gait speed as a functional measure of lower extremity were adopted as covariates. For gait speed, which was introduced to eliminate the confounding of the lower extremity dysfunction, a trained tester asked the participants to walk once along an 11-meter straight walkway on a flat surface at their usual pace, and then to walk twice along the walkway at the fastest and safest pace possible. Speed was calculated at a steady state by including only 5-meters of the center of the 11-meter pathway. The first and last 3-meters were considered as the acceleration and deceleration phases and were not included in speed calculation.

### ***Statistical analysis***

The participants' characteristics were summarized using mean and Standard deviation (SD) or frequencies and percentages, as appropriate. To examine the difference in clearances of leading and trailing limbs between young and older adults, repeated-measures ANOVA with two independent factors, i.e., limb (leading and trailing) and age-group (young and older adults), were performed adjusting for gender and the length of the lower limb. Furthermore, an ANCOVA adjusting for gender and the length of the lower limb including other parameters like the toe-obstacle distance, heel-obstacle distance, and variabilities in each parameter were performed to compare the young adults with older adults and reveal age-related behavioral difference in obstacle avoidance, except foot clearance.

To determine the degree of decrement in the clearance of the trailing limb compared with that of leading limb, the difference in clearance between the leading limb and trailing limb ( $\Delta$  clearance) was calculated with the following formula:  $[(\text{leading limb clearance} - \text{trailing limb clearance}) / \text{leading limb clearance} \times 100]$ , referring to a previous report<sup>17</sup>. Due to the observed multicollinearities among cognitive measures,

we performed partial correlation analyses (adjusting for gender, age, length of the lower limb, and gait speed) to examine the correlating cognitive factors for  $\Delta$  clearance. Similarly, partial correlation analyses adjusting for the aforementioned covariates were performed to examine respective associations among parameters of obstacle avoidance other than foot clearances and cognitive variables on the basis of all resultant significant age-related differences between young and older adults.

All statistical analyses were performed using the IBM SPSS Statistics, version 20.0 package (SPSS Inc., Chicago, IL, USA), and  $p$ -values less than 0.05 were considered statistically significant. To avoid type 1 error, a Bonferroni correction of  $p < 0.01$  was applied in each correlation analysis ( $p = 0.05/5$ , a number of cognitive assessments).

## Declarations

### *Competing interests*

The authors declare no competing interests.

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### *Author Contributions*

Dr. Sakurai structured the study design, performed statistical analyses, interpreted data, and drafted the manuscript. Dr. Kodama and Dr. Ozawa contributed to acquiring motion data and interpreted data. Dr. Ogawa contributed to acquiring cognitive data. Dr. Pieruccini-Faria and Dr. Kobayashi-Cuya interpreted data and helped finalize the manuscript.

### *Data Availability Statement*

The datasets analyzed during this study are available from the corresponding author upon reasonable request and after approval by institutional authorities.

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## Tables

**Table 1.** Participant characteristics.

<b>Variables</b>	<b>Young adults n = 103</b>	<b>Older adults n = 105</b>
Age, mean (SD)	27.4 (7.5)	78.2 (5.6)
Female, n (%)	55 (53.4)	86 (81.9)
Lower limb length, cm, mean (SD)	81.0 (4.9)	76.0 (5.4)
Gait speed, m/s, mean (SD)		1.36 (0.24)
MMSE (/30), mean (SD)		28.5 (1.7)
MoCA (/30), mean (SD)		25.6 (3.4)
TMT-A, s, mean (SD)		41.4 (55.1)
TMT-B, s, mean (SD)		116.6 (45.0)
LM: immediate (/50), mean (SD)		19.1 (7.3)
LM: delayed (/50), mean (SD)		13.9 (7.8)

Note: MMSE = Mini-Mental State Exam; MoCA = Montreal Cognitive Assessment; TMT = Trail Making Test; LM = logical memory subtest of the Wechsler Memory Scale.

**Table 2.** The differences in parameters of obstacle avoidance between young and older adults.

<b>Variables, mean (SE)</b>	<b>Young adults n = 103</b>	<b>Older adults n = 105</b>	<b><i>p</i>-value</b>
Variability in the LL clearance (CoV, %)	9.1 (0.5)	9.8 (0.5)	0.44
Variability in the TL clearance (CoV, %)	17.9 (1.0)	18.0 (1.0)	0.58
HO distance (mm)	293.8 (7.2)	179.8 (6.0)	<i>p</i> < 0.01
Variability in the HO distance (CoV, %)	11.1 (0.6)	17.2 (1.0)	<i>p</i> < 0.01
TO distance (mm)	143.0 (4.9)	160.1 (4.5)	<i>p</i> < 0.01
Variability in the TO distance (CoV, %)	18.9 (1.2)	16.0 (1.1)	0.06

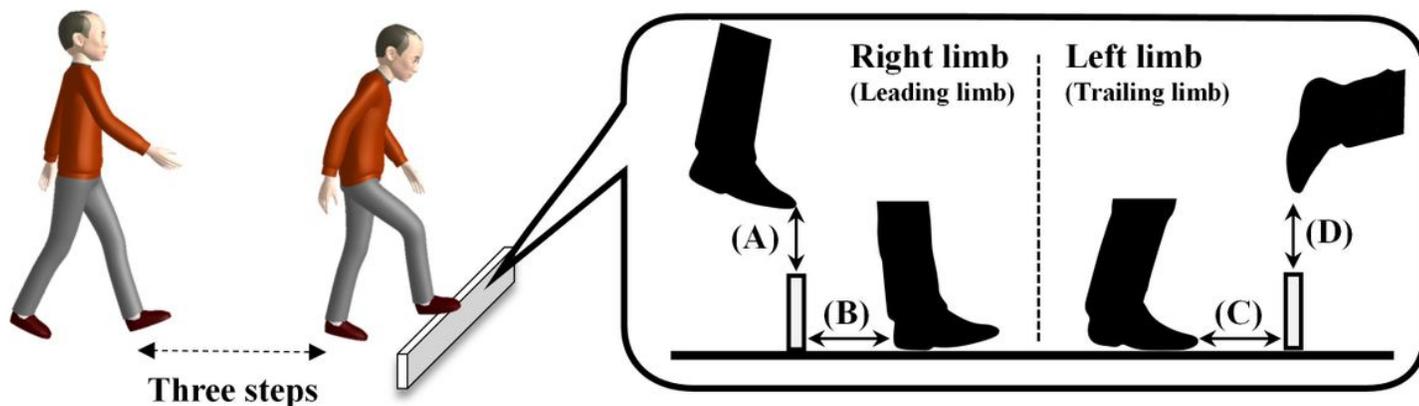
Note: LL = leading limb; TL = trailing limb; HO = Heel-obstacle; TO = Toe-obstacle; LM = logical memory subtest of the Wechsler Memory Scale

**Table 3.** Correlation coefficients among TO distance, HO distance, variability in the HO distance and cognition.

	MoCA	TMT-A	TMT-B	LM (immediate)	LM (delayed)
<b>HO distance</b>	-0.01 ( <i>p</i> = 0.94)	0.06 ( <i>p</i> = 0.53)	-0.03 ( <i>p</i> = 0.79)	-0.09 ( <i>p</i> = 0.38)	-0.15 ( <i>p</i> = 0.14)
<b>Variability in the HO distance</b>	0.071 ( <i>p</i> = 0.49)	-0.004 ( <i>p</i> = 0.97)	-0.116 ( <i>p</i> = 0.25)	0.083 ( <i>p</i> = 0.41)	0.067 ( <i>p</i> = 0.51)
<b>TO distance</b>	0.027 ( <i>p</i> = 0.79)	0.022 ( <i>p</i> = 0.83)	-0.003 ( <i>p</i> = 0.97)	0.084 ( <i>p</i> = 0.41)	0.167 ( <i>p</i> = 0.10)

Note: HO = Heel-obstacle; TO = Toe-obstacle; LM = logical memory subtest of the Wechsler Memory Scale

## Figures



**Figure 1**

Schematic illustration of obstacle avoidance task and parameters. (A) Leading foot clearance; (B) Heel-obstacle distance; (C) Toe-obstacle distance; (D) Trailing foot clearance

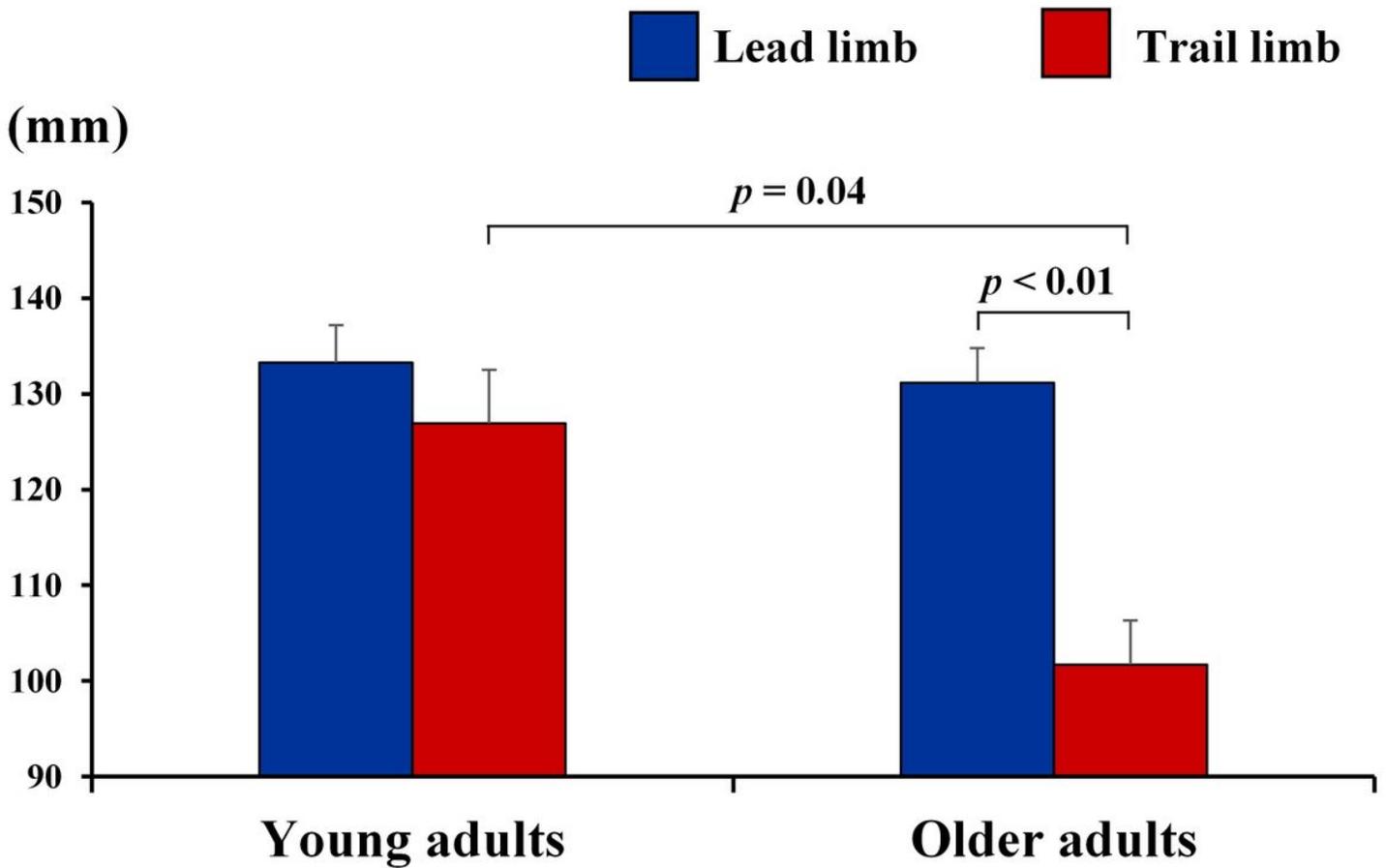


Figure 2

Comparisons of the leading and trailing limb clearances for young and older adults. Each comparison was adjusted by gender and the length of the lower limb. Bars and error bars indicate non-adjusted mean values and standard errors.

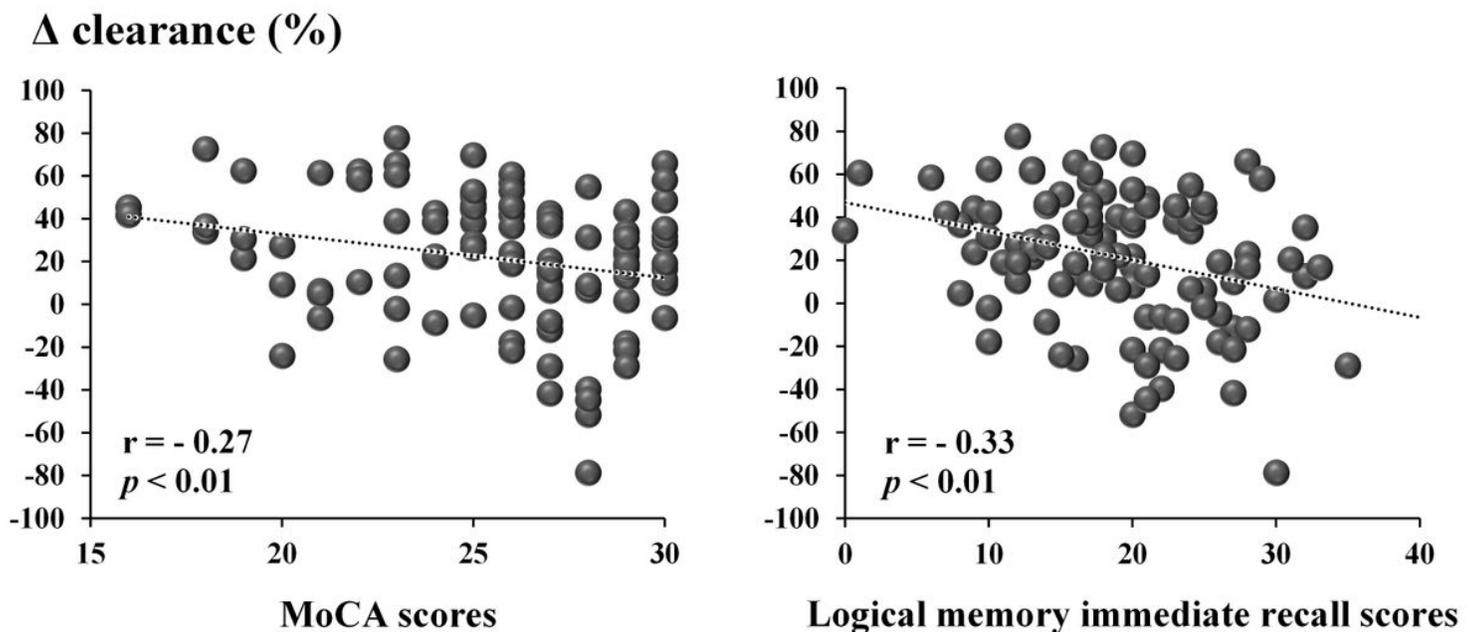
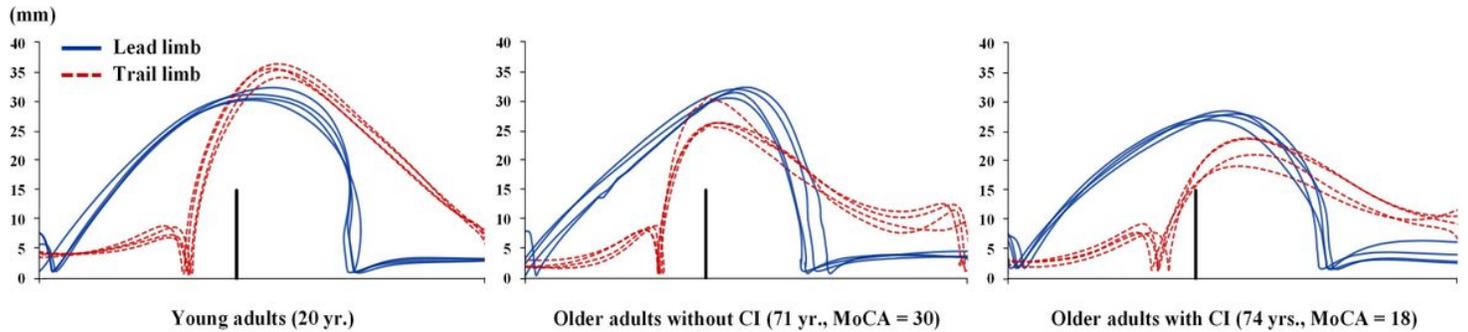


Figure 3

Scatter graphs of significant correlations between  $\Delta$  clearance and scores of cognitive assessments.  $\Delta$  clearance indicates the difference in clearance between the leading limb and trailing limb calculated with the following formula:  $[(\text{leading limb clearance} - \text{trailing limb clearance}) / \text{leading limb clearance} \times 100]$ . The positive  $\Delta$  clearance values represent lower clearance of the trailing limb compared to that of the leading limb. Corrected covariates include gender, age, length of the lower limb, and gait speed and a Bonferroni correction of  $p < 0.01$  was applied ( $p = 0.05/5$ , a number of cognitive assessments).



**Figure 4**

Typical toe trajectories in stepping-over an obstacle among young adults and older adults with and without significant cognitive impairments (they were all women). \*CI means cognitive impairments.