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Contribution of vision and its age-related changes to postural stability in obstacle crossing during locomotion

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Declaration of Interest

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Highlights

- We studied the role of visual fields in postural stability during obstacle crossing
- Postural instability during lead limb crossing was higher in older participants
- Visual occlusion did not affect postural stability regardless of age
- Near the obstacle, peripheral vision contributes little to postural stability
- However, information on the surrounding environment and the obstacle is required

Abstract

Background: Obstacle crossing requires sufficient toe clearance for trip and fall prevention for which postural stability is a prerequisite. It is thought that the upper visual field plays an important role in the maintenance of postural stability, but its influence and age-dependence have not been investigated yet.

Research question: What is the role of the visual fields in maintaining postural stability during crossing an obstacle in young and older adults?

Methods: This study included 14 young adults and 14 older adults. The participants, wearing an accelerometer and liquid crystal shutter goggles, were asked to cross an obstacle under the following three conditions: (i) full vision; (ii) total visual field occlusion at two steps before the obstacle, and (iii) lower visual field occlusion at two steps before the obstacle. The root mean square ratio in the mediolateral direction ($RMSR_{ML}$) for the three sections (i.e., approach to the obstacle, lead limb crossing, and trail limb crossing), as well as the root mean square in the mediolateral direction (RMS_{ML}) for each section were calculated.

Results: RMS_{ML} during lead limb crossing was significantly increased in older adults compared to young adults ($p<0.01$). There was no significant main effect of visual condition and age group on $RMSR_{ML}$ for the three steps.

Significance: The study results suggest postural lateral instability in older adults with poor balance ability during lead limb crossing. Regardless of age, the peripheral visual information appears to contribute minimally to the maintenance of postural lateral stability at least from two steps before the obstacle, when the participants perceived the surrounding environment and the size of the obstacle while approaching it.

Key words: vision, obstacle crossing, gait, older adults, postural stability, visual field

1. Introduction

Elderly people have many accidental falls, directly causing surges in medical expenses [1]. Environmental obstacles primarily lead to falls while walking [2]; thus, the visual perception of the environment is important [3]. To avoid obstacles during locomotion, obstacle crossing, which requires sufficient toe clearance (TC), is crucial.

The importance of visual information while approaching the obstacle was emphasized by a study examining the effects of visual occlusion on obstacle crossing during walking [4]. Moreover, visual information at two or more steps before the obstacle affects TC of the lead limb with no age-related changes in visuomotor control [5,6]. The lower visual field provides information on the foot trajectory during obstacle crossing [5,7], but the upper visual field plays an important role in the maintenance of postural stability [7].

To secure sufficient TC, posture stabilization is needed in obstacle crossing [8]. Studies reported that TC during obstacle crossing is significantly higher in older compared to younger adults [6,9]. Obstacle crossing also requires visuospatial memory and attention, which decline in older adults [10-12]. In addition, older adults have longer reaction times after a disturbance and poor adaptability to unexpected obstacle crossing/avoidance [3,13,14]. Thus, postural stability during obstacle crossing in older adults may depend more on visual stimuli compared to young adults. Despite evidence suggesting a role for vision in postural stability, the effect of visual information or peripheral vision during obstacle approach and crossing on postural stability has not been investigated. TC planning is made before the obstacle crossing. However, no study investigated whether visual information provided before or during motion plays an important role in the maintenance of postural stability during motion. In addition, safe motion requires the maintenance of postural stability in both obstacle crossing and in other sections, such as obstacle approach or lead and trail limb crossing. Thus, it is important to investigate the contribution of vision and its age-related changes to postural stability in obstacle crossing during locomotion.

Studies that measured postural stability, mainly using a 3D motion analyzer and a force plate, found that postural stability during obstacle crossing is impaired in older adults [15,16]. A 3-axis accelerometer is often used to evaluate postural stability during walking [17,18] with the root mean square (RMS) of trunk acceleration most often employed as an index to evaluate trunk stability [17]. Higher RMS (amplitude of the acceleration waveform) is generally associated with higher postural disturbance and risk of falls. The RMS ratio (RMSR; ratio of RMS for each direction axis to the RMS vector magnitude) allows assessment of lateral postural stability and is an index not affected by walking speed, which is required to assess fall risk [18]. Considering the increased lateral postural instability during obstacle crossing [16,19], the present study measured the mediolateral RMS and RMSR using a 3-axis accelerometer to evaluate postural stability during obstacle crossing.

Thus, the purpose of this study was to examine the role of the visual field and its age-related changes in maintaining postural stability during obstacle crossing (i.e., a series of motions such as approach to the obstacle, lead limb crossing, and trail limb crossing). We hypothesized that (1) TC will increase during visual occlusion two steps before the obstacle, (2) young adults will better maintain postural stability, and (3) older adults will have an increased postural disturbance during visual occlusion.

2. Materials and methods

2.1. Participants

Twenty-eight healthy people were divided into a young (n=14; seven males/seven females; mean age=21.7±1.7 years; age range=19–24; mean height=166.6±5.6 cm; mean mass=58.3±6.6 kg) and an older (n=14; seven males/seven females; mean age=68.7±2.8 years; age range=65–74; mean height=161.0±7.8 cm; mean mass=56.8±8.8 kg) adults group. There were no significant differences in height and mass between the two groups. All participants had normal vision, which was confirmed via an evaluation of past medical history, and were able to walk outside without glasses (only participants with normal vision and contact lenses were included). No participant reported visual difficulties, including those associated with distance perception, or any neuromuscular/orthopedic disorders that may have affected their participation in the study [6]. Young participants were recruited among the students at our university, and older adults were recruited from the Silver Human Resources Center.

All participants provided written informed consent. The present study was approved by our institutional ethics committee (approval number: 223) and conformed to the tenets of the Declaration of Helsinki.

2.2. Protocol

First, we assessed the participant's physical function using the Timed Up & Go test (TUG) and the Sit-to-Stand test (STS). In the TUG, we measured the time required to stand up from a sitting position, walk 3 meters, turn around, walk back, and sit down again. In the STS, the time required to stand with arms crossed was measured 10 times. A pressure-sensing mat (T.K.K.5806; Takei Equipment Co., Ltd., Tokyo, Japan) located on the seat of the chair was used for data collection. Each test was conducted twice, and the shortest time was taken as the representative value. In addition, the Visuo-Spatial Memory (VSM) test used by Maki et al. [20] was utilized to evaluate visuospatial memory capability. The Trail Making Test (TMT)-A and -B were used to examine attention.

Then, participants were asked to walk, at a self-selected pace, along a pathway with an obstacle, cross over the obstacle with the right foot, and continue walking for at least five additional steps (Figure 1). The start position was four or five steps before the obstacle. Participants practiced several times before the experiment. Gait analysis equipment (Walk Way MW-1000; Anima Co., Ltd., Tokyo, Japan) was used and one of two types of obstacles (depth=5 cm, width=70 cm, and heights=5 cm or 10 cm) was set up on the path. To increase contrast, the Styrofoam obstacles were red. For safety, they remained unfixed to the path. The motion was recorded using a digital camera (HDR-CX590V; SONY Corp., Tokyo, Japan) located on the side of the obstacle.

Participants were instructed to wear liquid crystal shutter goggles (S–13031; Takei equipment Corp., Ltd. Tokyo, Japan) and a foot switch on the right heel (fixed directly to the sock). With these goggles, participants' field of view is occluded in response to right heel contact. There were two types of goggles: one occluded the total visual field, whereas the other occluded only the lower visual field. In the latter case, the upper edge of the goggles was aligned with the pupil center, to prevent vision below this line. Participants were instructed to look straight ahead while walking to prevent head flexion. In addition, a wireless 3-axis accelerometer (MVP-RF8-GC-2000; MicroStone Co., Ltd, Nagano, Japan) was attached at the third lumbar level [17]. The acceleration signals were recorded at a sampling frequency of 200 Hz. We confirmed that the harness worn to protect participants had no effect on walking speed.

Participants were randomly asked to cross obstacles under three different visual conditions: (i) full vision, (ii) total visual occlusion at two steps before the obstacle, and (iii) lower visual occlusion at two steps before the obstacle [5,6]. The duration of visual occlusion lasted from the point of heel contact two steps before the obstacle to the point of heel contact three steps after the obstacle. To prevent falls, participants experienced visual occlusion one time before the trial while standing. The full-vision condition trial was carried out three times for each of the two goggles, and three trials were performed for each condition and each of the two obstacle heights (12 perturbed and 12 unperturbed trials). We evaluated the fear of visual-field occlusion after the final trial, by using a survey with a three-point scale.

2.3. Data analysis

Since participants were asked to cross the obstacle with the right foot, the right foot was defined as the lead limb and the left foot as the trail limb. The video data were converted into image data using motion analysis software (Media Blend; DKH. Co., Ltd, Tokyo, Japan.). Toe clearance of the lead limb (LTC) and the trail limb (TTC) were defined as the vertical distance from the front edge of the obstacle to the large toe of the lead and trail limb, respectively, during obstacle crossing.

We analyzed the acceleration for three steps, extending from two steps before the obstacle to one step after the obstacle. To clarify one step, the timing of the heel contact was identified from the front peak value in the anteroposterior direction waveform of the trunk acceleration [21, 22]. One step was defined as the distance from the heel contact to the next contralateral heel contact; we defined respective steps as an approach to an obstacle, a crossing over of the lead limb, and a crossing over of the trail limb. The acceleration data were analyzed using MATLAB, release 2018b (The MathWorks, Japan) and filtered by a 4^{th}-order Butterworth low-pass filter at 20 Hz [21]. The analyses in this study focused on lateral stability because several studies reported significant lateral postural disturbance during obstacle crossing in older adults and an age-related increase in lateral postural disturbance due to reduced physical functions [16,19]. RMSR and RMS for mediolateral trunk acceleration were calculated for three steps. The RMSR in the mediolateral direction ($RMSR_{ML}$) was calculated using the following formula with RMS in the anteroposterior direction (RMS_{AP}), RMS in the mediolateral direction (RMS_{ML}), and RMS in the vertical direction (RMS_V).

$$RMSR_{ML} = RMS_{ML} / \left(\sqrt{{RMS_{AP}}^2 + {RMS_{ML}}^2 + {RMS_V}^2} \right)$$

The RMS was calculated for each section. Because RMS has an exponential relationship with walking speed [17,22], it was normalized to the squared walking speed determined by the gait analysis equipment. The RMS in the approach section was defined as $RMS1_{ML}$, the crossing section of the lead limb was $RMS2_{ML}$, and the crossing section of the trail limb was $RMS3_{ML}$ (Figure 2).

Group differences in TUG, STS, VSM, and TMT results were analyzed using independent sample t-tests. LTC, TTC, and walking speed in obstacle-crossing gait were analyzed using a mixed-design analysis of variance model (ANOVA) for age (×2), visual condition (×3), and obstacle height (×2). To identify the section in which the postural disturbance increased, a mixed-design ANOVA with added section (×3) was additionally conducted for RMS. Bonferroni correction for multiple comparisons was used for post hoc analyses. All statistical analyses were conducted using SPSS Version 24.0J (IBM Corp., Japan), and the level of significance was set at $p<0.05$.

3. Results

3.1. TUG, STS, VSM, TMT, and fear of falling in obstacle crossing

Young adults had significantly better scores than older adults in all five tests (i.e., TUG, STS, VSM, TMT-A, and TMT-B) (Table 1). Throughout the experiment, no participant experienced fear of obstacle crossing.

3.2. LTC, TTC, and walking speed

For both LTC and TTC, there were significant main effects of age, visual conditions, and obstacle height (all $p<0.01$) (Table 2). A subsequent multiple comparison test revealed that LTC was significantly higher in older adults than in young adults ($p<0.01$). Furthermore, LTC was significantly higher under all visual-occlusion conditions compared to full-vision conditions (all $p<0.01$). There was no significant difference in LTC between total and low visual field occlusion. Moreover, LTC with 5 cm high obstacles was significantly increased compared to 10 cm high obstacles

($p<0.05$). The results for TTC were same as those for LTC. There was no significant main effect of walking speed for any measured parameter.

3.3. $RMSR_{ML}$ and RMS_{ML} for each section

There was no significant main effect of $RMSR_{ML}$ for any investigated factor. By contrast, a comparison of RMS_{ML} in each section revealed a significant interaction between age group and section ($p<0.01$) (Table 2). A subsequent multiple comparison test revealed that $RMS3_{ML}$ was significantly increased among all RMS values (all $p<0.01$), whereas $RMS2_{ML}$ was significantly higher than $RMS1_{ML}$ ($p<0.01$), regardless of age. $RMS2_{ML}$ was also significantly increased in older adults compared to young adults ($p<0.01$). There was no significant main effect or interaction of obstacle height and visual condition in $RMSR_{ML}$ and any RMS_{ML}.

4. Discussion

In the present study, LTC was affected by the visual condition. Our results (i.e., LTC is higher during visual occlusion) are consistent with those of previous studies [5,6]; the current results suggest that the lower visual field provides information regarding the relative position of the foot with respect to the obstacle and the trajectory of the crossing limb. Our study found no significant difference in LTC between total and lower visual field occlusion. Thus, the upper visual field is seemingly not involved in LTC control. However, the upper visual field seems to play an important role in maintaining postural stability [7]. Moreover, the results for TTC and LTC were similar, and TTC seems to be regulated by feedback from lead limb motion. In the current study, TC was significantly higher in older adults than in young adults, as reported previously [6,9], probably due to age-related decline in lower limb muscle strength and position perception. However, foot rising should increase postural instability. Thus, we considered RMS next.

In the current study, $RMSR_{ML}$ did not change with age or visual condition; it was possible to maintain postural stability during obstacle crossing without lower visual field information on the lower limb trajectory and optic flow [23] in the upper visual field. Based on previous findings that older adults have longer reaction times during disturbance [3,13,14] and have an increase in lateral postural instability during obstacle crossing with insufficient visual information [24], we hypothesized that visual occlusion increases $RMSR_{ML}$. However, our study results do not support this hypothesis. Previous findings [25-28] suggest that in a safe or familiar environment, lack of visual information has little effect on the dynamic control of postural stability, regardless of age. McKenzie et al. [28] report that obstacle crossing speed declines in older people due to increased fear, and it is thought they are also influenced by fear caused by visual disturbance. In the current study, no participant expressed a fear of falling. Moreover, the walking speed did not significantly differ between young and older adults, and visual occlusion did not reduce walking speed. Thus, perhaps even older adults with poor visuospatial memory and attention can maintain postural stability during obstacle crossing with visual occlusion if they perceive the surrounding environment adequately and feel safe.

In our study, RMS_{ML} was regardless of age significantly higher in the crossing lead and trail limb compared to the obstacle approach section. Longer one-leg standing time during obstacle crossing reportedly leads to an increase in the lateral shift of the mass center [9,16,24]. Thus, the amplitude of lateral postural acceleration is higher in the lead and trail limb crossing sections than in the obstacle approach section, increasing the probability for postural instability. The results of the current study support these findings. Moreover, RMS_{ML} was at maximum during trail limb crossing. We have found only a few studies investigating postural stability during trail limb crossing [11,12]. According to these studies, the trail limb is controlled without visual information creating the possibility to stumble over an obstacle. In addition to these reports, our study also suggests the possibility that postural stability may be reduced, thus increasing the fall risk during trail limb crossing.

RMS_{ML} during lead limb crossing was also significantly higher in older adults than in young adults. It has been reported that lateral postural instability during obstacle crossing is higher in older adults (especially those with poor balance ability) than in young adults [16,19]. It was suggested that older adults bend the trunk more laterally to maintain LTC, and this might have caused the higher RMS_{ML}.

However, as observed in $RMSR_{ML}$, visual occlusion did not affect RMS_{ML} in any section. This suggests that visual dependence of postural stability does not change among sections. Participants may have been able to maintain postural stability during obstacle crossing without visual information because they perceived the approximate size of the obstacle while approaching it [29]. However, LTC was increased probably because they did not know their relative position with respect to the obstacle. Thus, the lower visual field provides during obstacle crossing information on the relative position of the foot with respect to the obstacle and enables the control of LTC. Our results also suggested that access to visual information regarding obstacle size and surrounding environment while approaching the obstacle reduces the contribution of peripheral visual information to postural stability.

In our study, visual occlusion was random, but due to the characteristics of the research, it was possible for the study participants to prepare for the possibility of visual occlusion. As participants were expecting visual occlusion, there was a possibility that they consciously concentrated on proprioceptive instead of visual inputs, to maintain postural stability [8]. The obstacle material also differed from that in everyday life [30]. Therefore, the study results may slightly diverge from the contribution of visual information in common situations, such as the unexpected appearance of an obstacle or the movement in dark, unfamiliar environments. Furthermore, this study used typical obstacles with heights of 5 and 10 cm that are common in everyday life. It has been reported that with increased obstacle height, postural instability increases in older adults [9]. Future studies should additionally examine older adults with poor balance ability (e.g., difficulty with one-leg standing), history of falls, or fear of falls, to contribute to fall prevention in older adults. They should also investigate the foot trajectory [14].

5. Conclusion

Postural lateral instability during lead limb crossing was significantly increased in older adults than in young adults. Postural lateral stability during trail limb crossing was significantly lower compared to that during the approach section and the lead limb crossing section. The contribution of vision to dynamic postural stability tends to generally increase with age. However, this study found that access to visual information on the surrounding environment or the obstacle size during obstacle approach enables the maintenance of postural stability during obstacle crossing, regardless of age. Peripheral visual information appears to contribute minimally to the maintenance of postural lateral stability, at least from two steps before the obstacle. However, recognition of the obstacle location and LTC control require information from the lower visual field.

Conflict of interest statement

None.

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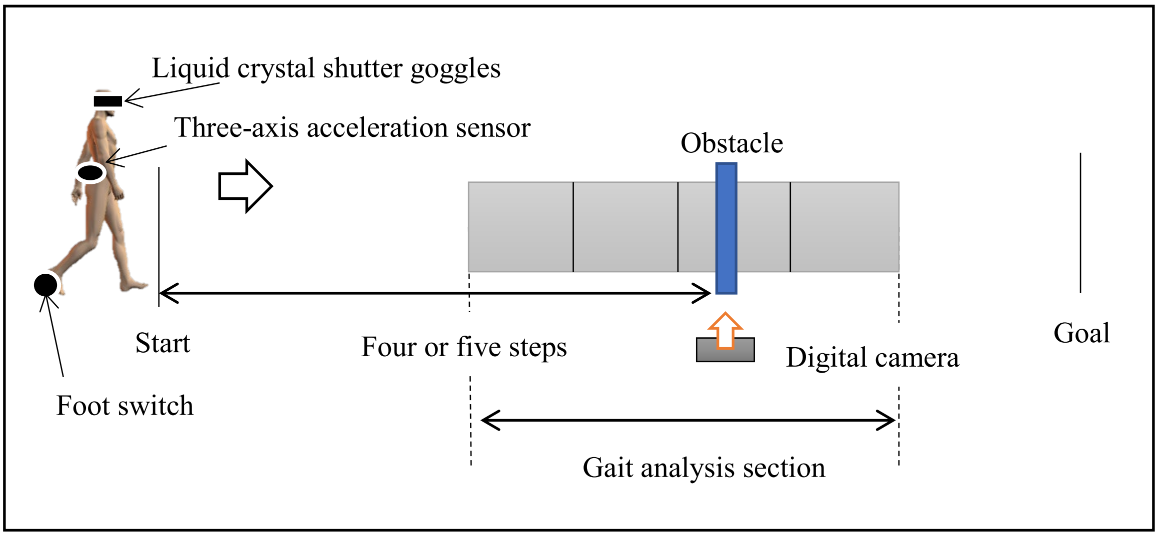

Figure 1

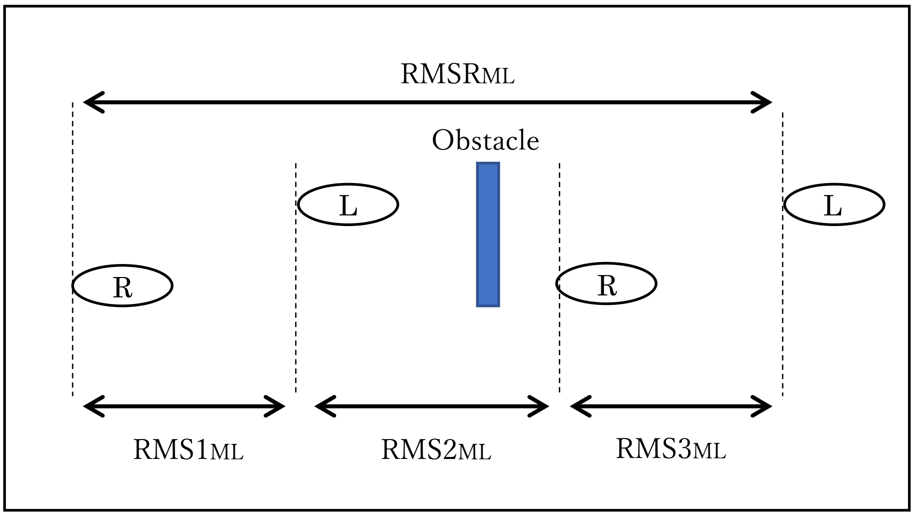

Figure 2

Figure 1. Experimental environment. Participants wore liquid crystal shutter goggles, a 3-axis accelerometer, and a foot switch. The timing of visual occlusion can be adjusted by setting the number of pressure stimuli applied to the foot switch.

Figure 2. Acceleration analysis of each section. Acceleration during three steps (i.e., starting at two steps before the obstacle, and ending at two steps after the obstacle) was analyzed. RMS was calculated from the acceleration data for these three steps. RMS was also calculated for each section. $RMS1_{ML}$, $RMS2_{ML}$, and $RMS3_{ML}$ were defined as the section of approach to the obstacle, the section of lead limb crossing, and the section of trail limb crossing, respectively. R: right foot; L: left foot.

Table 1. Participants' physical functions

	Young adults	Older adults	p value
TUG (s)	4.77 ± 0.68	6.94 ± 0.98	<0.01
STS (s)	10.39 ± 1.82	16.84 ± 4.35	<0.01
VSM	8.11 ± 1.06	5.96 ± 0.94	<0.01
TMT-A (s)	44.50 ± 7.28	92.43 ± 23.57	<0.01
TMT-B (s)	49.54 ± 9.50	106.71 ± 28.97	<0.01

Group mean values of TUG, STS, VSM, TMT-A, and TMT-B in young and older adults are shown. TUG: Timed Up & Go test; STS: Sit to Stand test; VSM: Visuo-Spatial Memory test; TMT: Trail Making Test.

Table 2. Each parameter during obstacle crossing

Conditions		full vision		total visual field occlusion		lower visual field occlusion		p value of main effect and interaction
Obstacle height (cm)		5	10	5	10	5	10	
LTC (cm)	YA	9.10±2.34	8.18±2.74	10.20±2.34	9.32±2.73	10.3±3.27	9.26±2.61	p_a<0.01‡, p_h<0.01§, p_c<0.01*†
	OA	13.58±2.99	13.26±3.86	14.95±3.35	14.54±4.75	14.89±3.20	14.84±4.49	
TTC (cm)	YA	6.73±1.80	4.81±2.00	7.60±2.06	5.61±2.35	7.87±2.90	6.24±2.98	p_a<0.01‡, p_h<0.01§, p_c<0.01*†
	OA	11.25±4.46	9.97±6.80	12.74±5.55	11.11±6.92	12.54±6.06	10.07±5.30	
walking speed (m/s)	YA	1.07±0.14	1.09±0.15	1.10±0.13	1.07±0.13	1.07±0.17	1.07±0.17	
	OA	0.89±0.14	0.92±0.14	0.91±0.14	0.90±0.14	0.93±0.17	0.93±0.17	
$RMSR_{ML}$ (m/s^2)	YA	0.42±0.07	0.43±0.07	0.42±0.06	0.42±0.07	0.44±0.08	0.43±0.08	
	OA	0.42±0.09	0.43±0.07	0.43±0.09	0.43±0.08	0.42±0.06	0.43±0.06	
$RMS1_{ML}$ (m/s^2)	YA	0.98±0.37	0.99±0.37	0.96±0.33	0.97±0.36	1.04±0.34	1.03±0.34	$p_{s×a}$<0.01¶ (RMS1–RMS3)
	OA	1.34±0.48	1.27±0.33	1.27±0.44	1.32±0.38	1.23±0.40	1.21±0.34	
$RMS2_{ML}$‡ (m/s^2)	YA	1.14±0.27	1.16±0.29	1.11±0.23	1.21±0.28	1.18±0.30	1.25±0.32	
	OA	1.58±0.48	1.59±0.53	1.59±0.45	1.71±0.56	1.53±0.47	1.65±0.65	
$RMS_{ML}3$ (m/s^2)	YA	1.66±0.73	1.73±0.91	1.53±0.65	1.71±0.83	1.77±0.79	1.88±0.98	
	OA	1.86±0.62	1.88±0.61	1.87±0.61	1.95±0.66	1.86±0.65	1.85±0.67	

Mean values of each parameter during obstacle crossing (i.e., LTC, TTC, walking speed, $RMSR_{ML}$, $RMS1_{ML}$, $RMS2_{ML}$, and $RMS3_{ML}$) by condition, obstacle height, and age group are shown. YA: young adults; OA: older adults; LTC: toe clearance of the lead limb; TTC: toe clearance of the trail limb; RMS_{ML}: root mean square in mediolateral direction; RMSR: RMS ratio; p_a: main effect of age group; p_h: main effect of obstacle height; p_c: main effect of condition; $p_{s \times a}$: interaction between section and age group; *: significant difference between full-vision condition and total-visual field occlusion condition ($p<0.01$); †: significant difference between lower-visual field and total-visual field occlusion conditions ($p<0.01$); ‡: significant difference between age groups ($p<0.01$); §: significant difference between obstacle heights; ¶: significant difference between RMS1 and RMS2, between RMS1 and RMS3, and between RMS2 and RMS3 (all $p<0.01$).