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Original Article

Influence of history of falls and physical function on obstacle-straddling behavior

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Abstract. [Purpose] This study aimed to clarify the relationship between falls and lower leg motion during obstacle crossing, in which stumbling or tripping is the most common cause of falls in the elderly population. [Participants and Methods] This study included 32 older adults who performed the obstacle crossing motion. The heights of the obstacles were 20, 40, and 60 mm. To analyze the leg motion, a video analysis system was used. The hip, knee, and ankle joint angles during the crossing motion were calculated by the video analysis software, Kinovea. To evaluate the risk of falls, one leg stance time and timed up and go test were measured, and data on fall history were collected using a questionnaire. Participants were divided into two groups: high-risk and low-risk groups, according to the degree of fall risk. [Results] The high-risk group showed greater changes in hip flexion angle in the forelimb. The hip flexion angle in the hindlimb and the angle change of lower extremities among the high-risk group became larger. [Conclusion] Participants in the high-risk group should lift their legs high when performing the crossing motion to ensure foot clearance and avoid stumbling over the obstacle.

Key words: Obstacle avoidance, Fall risk, Joint angle

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INTRODUCTION

Approximately 30% of people >65 years fall each year[1)], about half of whom have recurrent falls[2)]. Of 261 falls among older adults aged ≥65 years, the most severely injured body part was the head, followed by the hip[3)]. Moreover, approximately 5.5% of elderly patients diagnosed with fall-related hip fractures die during hospitalization[4)]. Humans have several options for avoiding obstacles during walking. For example, their options include changing course and moving the obstacle. One of the most common risks for falling in the elderly population is to cross over an obstacle[5)]. Falling in the elderly may cause hip fracture, spinal cord injury, and head injury. The most frequent reasons for falling are tripping or stumbling[6, 7)]. According to a previous study[8)], 47.3% of fall accidents happened during walking, and these accidents were mostly induced by tripping or slipping. According to another study on the reasons for falling in 60- to 80-year-olds, 59% of people tripped or slipped[9)]. Since tripping is one of the most common reasons for falling, it is necessary to clarify the causes of tripping during the crossing motion.

To cross over an obstacle safely, it is necessary to properly adjust the landing place. One study concluded that strides increased and decreased depending on the situation or characteristics of the individual[10)]. Regarding the adjustment of stride, young adults tended has been reported to extend their stride as they got closer to the obstacle, while older adults tended to reduce it[11)]. Thus, there may be some age-related differences in the abilities of adults to adjust their strides according to their situations.

A previous study of obstacle crossing during a walk highlighted that stride and foot clearance had been the focus in the past. In addition, a study indicated that the step adjustment had to be done before reaching the obstacle during walking[12)].

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To adjust stride and avoid obstacles, visual information is essential. In terms of visual information processing, humans see an obstacle a couple of steps before crossing it, and they do not see the obstacle at the moment of crossing over[13]. This means that visual information processing finishes before the crossing motion. Therefore, to select the proper motion strategy, it is necessary to process visual information and adjust stride.

Regarding the center of mass (COM) during the crossing motion, vertical displacement has been shown to become large depending on the obstacle height[14]. Moreover, the landing position of the foot reportedly influences the COM displacement[15]. Many studies have focused on foot clearance during the crossing motion. Foot clearance has been shown as adjusted to minimize the distance between the foot and an obstacle[16]. Chen et al. reported that there were no significant differences in clearance based on the different heights of obstacle crossings between the young and the elderly[11].

One study revealed that obstacle avoidance was conducted based on the stride in advance and that there were no significant differences in clearance between younger and older adults. However, the strategy of the crossing motion is based on the physical function of the elderly. We believe that different physical functions require different exercise strategies because older adults who are at higher risk of falling may have different exercise strategies due to reduced lower limb function and insufficient support when stepping over obstacles. Therefore, this study aimed to clarify the parameters influencing fall risks based on physical function associated with the obstacle crossing motion. Based on the results of this study, we can predict fall risk by evaluating the crossing motion and physical function.

PARTICIPANTS AND METHODS

This study included 32 older adults without cognitive decline or serious problems with their trunks or lower extremities in a community long-term care prevention class. All participants did not have any orthopedic disease, osteoporosis, neurological disease, dementia that could affect gait, and any equilibrium function disorder that could affect gait performance. In addition, all participants had no history of pain-related gait changes, fractures, or hospital treatment after a fall.

The inclusion criteria were the ability to walk independently without assistance, hearing capacity sufficient to perceive auditory cues, and the absence of significant cognitive impairment (Fig. 1). The sample size was calculated using G*power 3.1.9.7 (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany), and the configuration was as follows: effect size=0.4 and power=0.8. Participants were informed with a written explanation of the experimental purpose, procedures, potential risks, and the right to refuse inclusion in the study. All participants provided their written informed consent for participating in this study. The experimental procedures were approved by the ethical committee of the International University of Health and Welfare (21-Ig-202).

Participants were asked to cross over an obstacle after walking a 7 m course (Fig. 2). The obstacle consisted of styrofoam. The heights of the obstacles were 20, 40, and 60 mm. Participants performed crossing tasks three times for each of the three conditions. They were also asked not to focus on particular objects.

Two digital video cameras, HDR-CX535 (Sony, Tokyo, Japan), were used to capture information that is 60 Hz from the sagittal plane for the crossing motion. Figure 2 indicates the placement of the cameras. Reflective markers were placed on both sides of the acromion (shoulder marker), great trochanter (hip marker), the lateral gap of the knee joint (knee marker), lateral malleolus (ankle marker), and the head of the fifth metatarsal bone (toe marker). To calculate the joint angle, we used the software, Kinovea, version. 0.9.5 (Kinovea, Bordeaux, France). The leg which crossed over first was defined as the proceeding leg (PL), and the leg which crossed over next was defined as the subsequent leg (SL). The hip, knee, and ankle angles during the crossing motion were calculated, and the averages of three measurements were adopted. The calculation

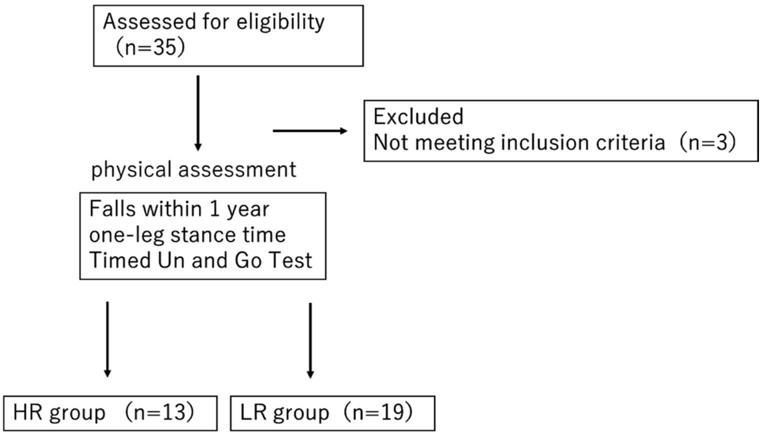

Fig. 1. Flow diagram of this study.
HR: high-fall-risk group; LR: low-fall-risk group.

points were at the mid-swing phase of PL (MS-phase), the time when the marker of PL was right above the obstacle (PL-RA-phase), and the time when the marker of SL was immediately above the obstacle (SL-RA-phase) (Fig. 3). The line connecting the shoulder and hip markers was defined as the trunk, the hip and knee marker as the thigh, the knee and foot marker as the lower leg, and the ankle and toe marker as the foot. The angle of the trunk and thigh was calculated as the hip angle, the thigh and lower leg as the knee angle and the lower leg and foot as the ankle angle. Moreover, the time of the stance phase of the support leg during the crossing (step time) was calculated by the movie (Fig. 4). The validity and reliability of the calculation method of the joint angle using Kinovea were confirmed by previous reports17, 18).

To evaluate the physical function, we measured this value using the Timed Up and Go Test (TUG)19) and the one-leg stance time20). We also obtained information on fall history using a questionnaire. A person who had fallen even once within the previous 1 year was defined as a faller. According to this evaluation, we classified the low-fall-risk group (LR) and the high-fall-risk group (HR). TUG and one-leg stance time were measured twice, and the one with the better result was adopted. TUG is a test of walking time that combines standing up from a chair, walking for 3 m, turning, walking back, and sitting down. The test has developed as an evaluation of mobility and screening for fall risk. Participants can walk at any speed and direction. We set the cutoff for 13.0–13.5 s as the definition. The one-leg stance time was measured as a postural ability

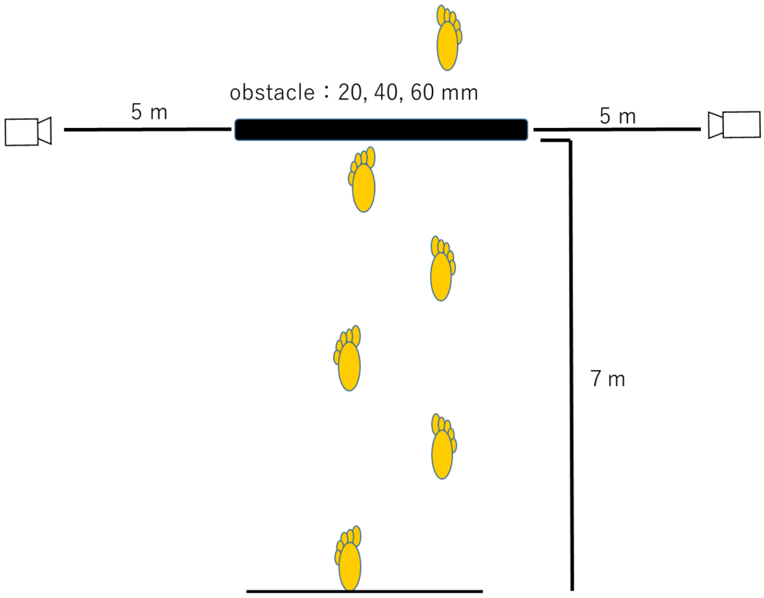

Fig. 2. Experimental setup.

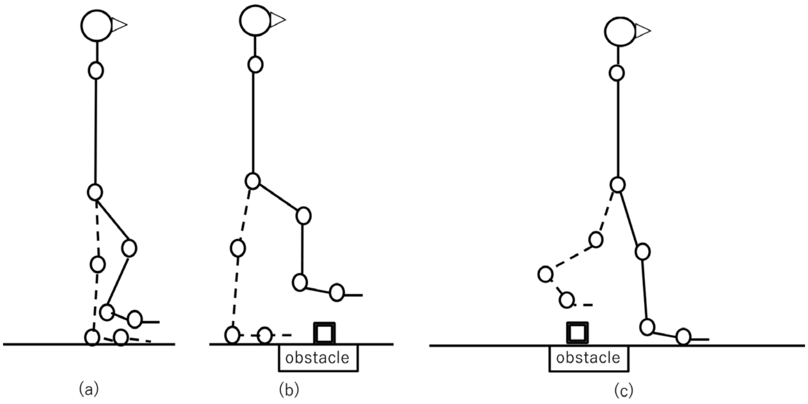

Fig. 3. Calculation points.
(a) Mid-swing of the PL (MS-phase), (b) Right above the obstacle of the PL (PL-RA-phase), (c) Right above the obstacle of the SL (SL-RA-phase).
PL: proceeding leg; SL: subsequent leg.

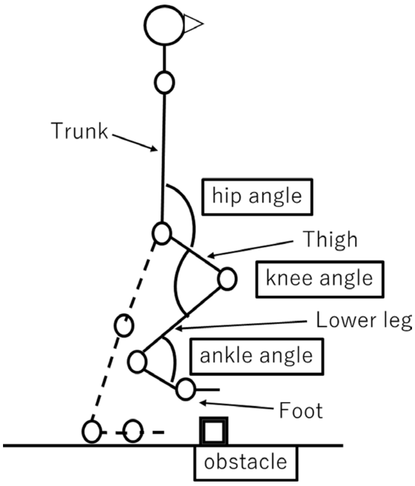

Fig. 4. Angle definition.

evaluation. Participants held their arms on their waists and kept their feet away from the floor without a supporting tool. We measured the one-leg stance time with both eyes open, considering the risk of falling. We recorded the time up to 60 seconds maximally. We set the cutoff time for under 5 s according to a previous study[21].

In terms of statistical analyses, the Shapiro–Wilk test was performed to confirm normality, followed by a two-way ANOVA [two groups; HR group vs. LR group × three kinds of obstacle heights (20 × 40 × 60 mm)]. Analyses were performed using SPSS Statics 25 (IBM Corp, Armonk, NY, USA). Statistical significance was set at $p<0.05$. P-value and effect size ($\eta^2=SS_{\text{Effect}}/SS_{\text{Total}}$) were also calculated.

RESULTS

Table 1 indicates the results of the physical function evaluation. The numbers for the HR and LR groups were 13 and 19, respectively. The one-leg stance time of the LR group was significantly shorter than that of the HR group (p=0.04). The TUG time of the LR group was significantly shorter than that of the HR group (p=0.01). The number of fallers during the previous year was 8.

Table 2 indicates the angle changes during the mid-stance phase of the PL. In terms of the maximum hip flex angle, a significant main effect was found (F=15.26, p=0.002, $\eta^2=0.13$). Similarly, a significant main effect for the obstacle height was found (F=4.76, p=0.01, $\eta^2=0.08$). Meanwhile, there was no significant main effect between the groups with respect to the maximum knee flex angle of the PL, although a significant main effect was found between the 20, 40, and 60 mm heights (F=18.22, p=0.0001, $\eta^2=0.27$). Significant differences in the maximum ankle angle of the PL were not observed.

Table 3 indicates the joint angle changes of the PL-RA-phase. In terms of the maximum hip flex angle, a significant main effect was found (F=9.30, p=0.003, $\eta^2=0.07$). Similarly, a significant main effect for the obstacle height was found (F=18.22, p=0.0001, η2=0.27). Significant main effects were not found for the maximum knee flex angle between the groups; however, significant main effects were found (F=15.46, p=0.0001, η2=0.26), such that the higher the obstacle became, the larger the knee angle was.

Table 4 indicates the results of the joint angle changes of the SL-RA-phase. In terms of the maximum hip flex angle, a significant main effect was found (F=12.31, p=0.0007, $\eta^2=0.12$). Significant main effects were not found for the maximum knee flex angle between the groups; however, significant main effects were found (F=8.17, p=0.0005, $\eta^2=0.15$), such that the higher the obstacle became, the larger the knee angle was. Significant differences in the maximum ankle angle of PL were not observed.

Table 1. Physical evaluation

	HR group (n=13)	LR group (n=19)
Gender (male/female)	4/9	4/15
Age (years)	76.2 ± 5.5	74.6 ± 4.4
Height (cm)	158.2 ± 6.6	156.6 ± 6.6
Weight (kg)	55.3 ± 8.6	52.4 ± 7.7
Number of fallers (person)	8	0
One-leg stance (sec)	18.2 ± 20.1	45.9 ± 18.9*
TUG (sec)	9.0 ± 1.5*	7.6 ± 1.2

*p<0.05.
HR: high-fall-risk group; LR: low-fall-risk group; TUG: timed up and go test.

Table 2. The angle changes of MS-phase (°)

MS-phase		HR	LR
Hip flex	20 mm	36.93 ± 8.94¶**	30.19 ± 5.17
	40 mm	41.99 ± 6.94¶**	34.60 ± 9.06
	60 mm	44.10 ± 9.77¶** †**	36.72 ± 9.78†**
Knee flex	20 mm	71.13 ± 7.27	72.86 ± 7.21
	40 mm	79.10 ± 12.90†**	81.17 ± 11.05†**
	60 mm	85.34 ± 10.00†** ‡**	86.45 ± 9.47†** ‡**
Ankle plantar flex	20 mm	5.91 ± 8.34	8.53 ± 7.39
	40 mm	7.60 ± 7.10	5.35 ± 7.16
	60 mm	5.22 ± 8.64	7.01 ± 8.06

**p<0.01 † vs. 20 mm ‡ vs. 40 mm ¶ vs. LR.
MS: mid-swing; HR: high-fall-risk group; LR: low-fall-risk group.

Table 5 shows the results of the step time. No significant interaction effects were found; however, significant main effects were found between the groups ($F=7.88$, $p=0.0062$, $\eta^2=0.08$).

DISCUSSION

According to the results of this study, the HR group flexed the hip joint larger than the LR group when trying to avoid obstacles. Moreover, the LR group might avoid obstacles while maintaining walking speed with minimal joint angle changes. We observed that the HR group lowered walking speed, extended the one-leg stance time, and raised the leg during the crossing motion. As a result, the HR group flexed the hip joint of the PL, crossed over the obstacle, and adequately maintained foot clearance. Similarly, the hip joint of the SL was also flexed larger than that of the LR group. Therefore, we suggest that the HR group tends to select the characteristic strategy which uses hip flexion (both PL and SL) larger than that of the LR group.

Regarding the reason for the motion strategy of the HR group, we believe that this group adjusted the stride before the crossing. To cross over an obstacle safely, it is necessary to land the crossing foot at a proper place22). A previous study reported that both younger and older adults adjusted their strides just before crossing during walking12, 22). Regarding the

Table 3. The angle changes of PL-RA phase (°)

PL-RA-phase		HR	LR
Hip flex	20 mm	45.63 ± 8.56¶**	40.82 ± 6.78
	40 mm	53.86 ± 7.27¶** †**	48.42 ± 9.19†**
	60 mm	60.82 ± 10.22¶** †** ‡*	53.67 ± 10.41†** ‡*
Knee flex	20 mm	43.56 ± 11.02	44.21 ± 14.20
	40 mm	58.44 ± 11.54†**	56.29 ± 14.65†**
	60 mm	63.93 ± 15.96†**	64.07 ± 15.09†**
Ankle plantar flex	20 mm	11.07 ± 8.09	10.38 ± 7.60
	40 mm	11.25 ± 10.95	8.58 ± 7.74
	60 mm	11.78 ± 10.59	7.11 ± 7.15

**p<0.01; * p<0.05; † vs. 20 mm; ‡ vs. 40 mm.
PL-RA: when the marker of PL was right above the obstacle; HR: high-fall-risk group; LR: low-fall-risk group.

Table 4. The angle changes of SL-RA-phase (°)

SL-RA-phase		HR	LR
Hip flex	20 mm	25.15 ± 6.44¶**	21.50 ± 6.77
	40 mm	26.71 ± 8.29¶**	20.91 ± 6.63
	60 mm	30.13 ± 8.04¶**	23.55 ± 6.63
Knee flex	20 mm	78.90 ± 9.72	81.87 ± 9.64
	40 mm	84.46 ± 7.61	83.18 ± 8.96
	60 mm	91.37 ± 10.35†** ‡*	88.30 ± 7.39†** ‡*
Ankle plantar flex	20 mm	16.97 ± 10.68	17.77 ± 6.40
	40 mm	14.93 ± 9.23	18.07 ± 8.23
	60 mm	17.60 ± 15.19	18.86 ± 9.98

**p<0.01; *p<0.05; † vs. 20 mm; ¶ vs. LR; ‡ vs. 40 mm.
SL-RA: when the marker of SL was immediately above the obstacle; HR: high-fall-risk group; LR: low-fall-risk group.

Table 5. Step time (s)

Step time	HR	LR
20 mm	0.57 ± 0.09¶**	0.54 ± 0.04
40 mm	0.59 ± 0.07¶**	0.56 ± 0.04
60 mm	0.61 ± 0.06¶**	0.57 ± 0.04

**p<0.01; ¶ vs. LR.
HR: high-fall-risk group; LR: low-fall-risk group.

adjustment of stride, older adults tend to adopt a strategy that reduces their strides immediately before the crossing, while young adults adopt a strategy that extends their strides[11, 23)]. We believe that the reduction of the stride in the elderly causes a decrease in walking speed and extends the step time and elevation of the leg higher than those in young adults.

According to the results of the angle changes during the mid-swing of PL, the hip flex angle change of the HR group was larger than that of the LR group. Patla et al. reported that the joint angle changes of the swing leg related to foot clearance[24)]. It is likely that older adults with a history of falls chose the strategy of allowing more room between the foot and the obstacle as a preventive measure against a potential fall due to the influence of fear of falling. We believe that older adults with a history of falls choose a strategy of maintaining more margin between the foot and the obstacle as a precaution against falling. Therefore, we also believe that the increase of the hip angle change causes sufficient foot clearance for avoiding the obstacle.

Chou et al. reported that the higher the obstacle becomes, the higher the COM increase for the crossing motion[14)]. Similarly, Pan reported that the foot position influences COM movement during the crossing motion[25)]. Therefore, we suggest that the foot position be adjusted by the reduction of stride during the obstacle crossing motion, especially in the case of a high obstacle. Additionally, we believe that the increase in the joint angle changes of the leg for avoiding obstacles causes the elevation of COM.

In this study, the one-leg stance time of both sides of the HR group decreased because of lower leg hypofunction. Therefore, the propulsion to the anterior direction was insufficient, and the one-leg stance time of the HR group extended during the crossing motion compared with that of the LR group. Adequate activities of the knee extension muscles are needed for stance leg during walking[26)]; however, the HR group lacked postural control abilities and could not support stability. As a result of the one-leg stance time, it is speculated that the decline of muscle strength in the lower leg is weakened and could have induced the decrease of the propulsion of walking. Several reports have concluded that the decline of the planter-flex moment of the ankle joint is induced to slow down walking speed[27–29)]. Similarly, according to other studies, it is necessary to keep the propulsion to the anterior for proper obstacle crossing[23, 29)]. Therefore, we believe that the decline of the plantar-flex moment during the stance phase or the decrease of the one-leg stance time could extend to the step time. In other words, humans adjust their strides depending on the height of the obstacle crossing; however, in our study, the HR group could not maintain the walking speed because of a decrease in muscle strength. We found that the HR group would decelerate and keep the stance phase longer compared with the LR group, as they tend to flex their hip joint at a larger angle than the LR group to avoid collision with the obstacle.

This study had several limitations. We did not analyze the motion in the approach zone, and we did not calculate the force. In addition, we used the video analysis system, which can be performed in the field at any location and is the most commonly used method in clinical practice. However, it is less accurate than 3D motion analysis. Therefore, it is necessary to capture the results of a similar study using a three-dimensional motion analysis system consisting of more than five cameras and a force plate in the future.

In conclusion, the HR group avoided obstacles with hip dominance due to their slow speed when straddling obstacles. Maintaining the hip extension angle of the supporting leg and adequate walking speed to prevent excessive hip flexion is important for safe obstacle avoidance.

Conflict of interest

None.

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