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Original Article

Strategies for obstacle crossing in older adults with high and low risk of falling

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Abstract. [Purpose] Tripping is a frequent cause of falls among aging adults. Appropriate limb movements while negotiating obstacles are critical to trip avoidance. The aim of our study was to investigate the mechanics of obstacle crossing in older adults at low or high risk of falling. [Subjects and Methods] Twenty community-dwelling adults aged ≥55 years, were evaluated with the Tinetti Balance and Gait scale and classified as being at high or low risk of falling. Between-group comparisons of kinematics were evaluated for obstacle heights of 10%, 20%, and 30% of leg length. [Results] The high-risk group demonstrated greater toe-obstacle clearance of the leading leg. Increasing obstacle height led to increased maximal toe-obstacle clearance, toe-obstacle distance, and shortened swing phase of the leading limb. Adaptation of clearance height was greater for the trailing leg. Individuals at high risk of falling demonstrated less symmetry between the leading and trailing legs and a narrower step width, features that increase the likelihood of tripping. [Conclusion] Kinematic parameters of obstacle clearance, including the symmetry index described in our study, could provide clinicians with a quick screening tool to identify patients at risk of falling and to evaluate outcomes of training programs.

Key words: Symmetry index, Obstacle negotiation, Foot clearance

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INTRODUCTION

Falls and the fear of falling are among the most serious and common medical problems experienced by older adults, often leading to disability and morbidity[1)]. Fall-related injuries among older adults are also a significant source of increased health care resource needs and costs[2–4)]. Approximately 30–53% of community-dwelling adults, over the age of 65 years, experience one or more falls each year[5–10)].

The increased risk of falling with aging is multifactorial in nature and is influenced by age-related declines in balance and mobility function, as well as by the burden of multiple chronic diseases and disabilities. Factors attributed to an individual's risk of falling are generally evaluated at three levels: intrinsic factors, occurring at the level of the individual; extrinsic factors, occurring at the level of the environment; and activity-related factors[5, 8, 11–13)]. A number of intrinsic factors specifically correspond to the risk of falling, including gross impairments in balance and gait, cardiovascular dysfunction, neurological impairments, musculoskeletal conditions, limitations in general physical functioning, being female, chronic health conditions, and deconditioning following a prolonged period of bed rest or inactivity.

The Tinetti Gait and Balance Test (Tinetti test) is one component of the Performance Oriented Mobility Assessment (POMA) that was designed to evaluate gait and balance function in older individuals[14, 15)]. The Tinetti test is a simple tool that can easily be implemented in practice as a way to screen for risk of falling in older individuals. The test integrates an assessment of both balance function and gait. Balance is assessed by 14 items, which include a series of balance maneuvers such as

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quiet standing, moving from sitting to standing position, and turning 360°, providing a total balance score of 24 points. Gait function is assessed on a 10-item scale, providing a total score of 16 points. The total score on the Tinetti test ranges between 0 and 40 and higher scores are indicative of better balance and gait functions. The inter-rater and test-retest reliability of the Tinetti test is high, with agreement values of 95% for the balance and gait subscales[14)]. More importantly, the Tinetti test has high predictive reliability for falls and fall-related injuries among community-dwelling older adults and residents of intermediate care facilities[8, 14, 15)]. Using a cutoff score of 36, the Tinetti test has a sensitivity of 70% and specificity of 52% with the Berg Balance Scale. The time required to administer the balance and gait subscales (approximately 10 minutes) is less than the time required to administer the Berg Balance Scale[16)].

Balance impairments during walking and tripping while negotiating obstacles are most likely the two most common causes of falls in older adults[14, 17)]. A loss of balance while maneuvering an obstacle may cause sudden and inappropriate movements of the lower limbs that lead the foot to contact the obstacle rather than clear it. Experimental studies have demonstrated that the trajectory of the leading limb (i.e., the limb crossing the obstacle first) is modulated principally by the height of the obstacle, with negligible influence from the width of the obstacle. Obstacle height provokes significant adaptations of the degree of flexion at the hip, knee, and ankle[18–20)] and also modulates the kinematics of the trailing limb (i.e. the limb crossing the obstacle last), by increasing knee flexion during swing[21, 22)].

Temporal variables provide information about the time required to adjust the kinematics of the lower limbs for obstacle clearance. Duration of swing phase, measured from toe-off to foot contact, provides insight into the time required to prepare the limb for clearance and landing. Research has demonstrated a linear association between increasing obstacle height and prolonged swing phase duration[17, 21)]. Individuals who have sustained a stroke show an increased swing phase duration of the affected leading limb, which is indicative of the increased time required to modify trajectories and prepare for the clearance and landing phases[23, 24)]. Walking velocity is also a confounding factor that has been associated with falls in older adult populations[18, 23, 25–29)]. Compared to young adults, older individuals exhibit slower speed while navigating an obstacle[18, 30)]. Reduced walking speed has also been reported in individuals with a history of stroke or Parkinson's disease[23, 31)].

With regard to the design of preventive programs in primary health care, it is important to gain more insight into the relationships between the risk of falling and gait characteristics. In particular, the characterization of age-related changes in lower limb control and balance would provide a basis to understand, and therefore possibly mitigate, the effects of aging on the ability to safely negotiate obstacles. This is important, since difficulty negotiating obstacles is one of the key determinants that leads older adults to refrain from walking and participating within their community. Identifying key features of obstacle crossing may also provide clinicians with the information necessary to guide an assessment of dynamic balance and gait at the person-environment interface. The aim of our study was to investigate the mechanics of obstacle crossing in older adults assessed to be at either low or high risk of falling.

SUBJECTS AND METHODS

Twenty individuals over the age of 55 years were randomly selected from a community dwelling in Central Taiwan. All prospective participants walked independently without an assistive device at home and within the community, with no history of serious head trauma, cognitive impairment, neurological, orthopedic, cardiovascular, musculoskeletal, or pulmonary disorders, and no uncorrected visual impairment that would affect balance, gait, and overall physical function. None of the participants showed evidence of persistent symptoms of vertigo, lightheadedness, or unsteadiness. A cutoff score of 36 on the Tinetti Balance and Gait subscale of the POMA was used to classify participants as either at high or low risk of falling[16)]. Accordingly, 10 participants with a score below 36 were classified as the high-risk group, while the other 10 participants had scores over 36 and were classified as the low-risk group. The descriptive characteristics of the participants are listed in Table 1. Prior to testing, the purpose and procedures of the study were explained to participants and informed consent was obtained. A brief history was taken, and the participants' general health problems were recorded. A lower extremity scan was completed by a physical therapist to confirm the absence of lower limb injury or any impairment that could limit performance of the experimental tasks. Necessary demographic and anthropometrical data were recorded. The study protocols had been approved by the KAOHSIUNG V.G.H. Institutional Review Board (IRB No.: VGHKS99-CT1-02).

The Helen Hayes Marker Set was secured over selected anatomic landmarks to record lower limb motions during level and obstructed walking trials. Two additional markers were placed on the obstacle for the measurement of limb positions relative to the obstacle. Segmental motions were captured using VICON Motion Analysis System (Oxford Metrics Limited, UK) at a 60 Hz sampling rate. Obstructed walking trials were performed with bare feet along a 6 m walkway at a self-selected speed. The obstacle consisted of 2 adjustable upright struts with a padded crossbar that was placed at the midpoint of the walkway, with the height of the obstacle adjusted to 10%, 20%, or 30% of each participant's leg length (measured from the anterior superior iliac spine to the medial malleolus). Participants were instructed to walk forward in a straight line, step over the obstacle, and continue walking for at least 3 steps. The starting position was adjusted for each participant to ensure a minimum of 3 steps before reaching the crossing stride. Several practice trials were provided prior to data collection, and rest periods were provided, as necessary, throughout the session. Each participant completed 3 trials under each of the 3 experimental conditions: obstructed walking at 10%, 20%, and 30% obstacle height. The crossing stride used in the analysis was defined as the interval between the heel strike of the trailing leg before the obstacle to the heel strike of the same leg after

Table 1. Mean and standard deviation of subject's characteristics

Group	High risk (n=10)	Low risk (n=10)
Age (yrs)	62.5 ± 6.6	65.6 ± 8.7
Height (cm)	157.2 ± 8.7	159.5 ± 8.0
Weight (kg)	56.5 ± 9.0	57 ± 11.2
Leg-length (cm)	80.5 ± 4.8	81.5 ± 4.0
Tinetti gait	13.2/16 (± 2.0)	16/16 (± 0)
Tinetti balance	19.2/24 (± 4.9)	24/24 (± 0)
Tinetti scores	32.4/40 (± 6.4)	40/40 (± 0)

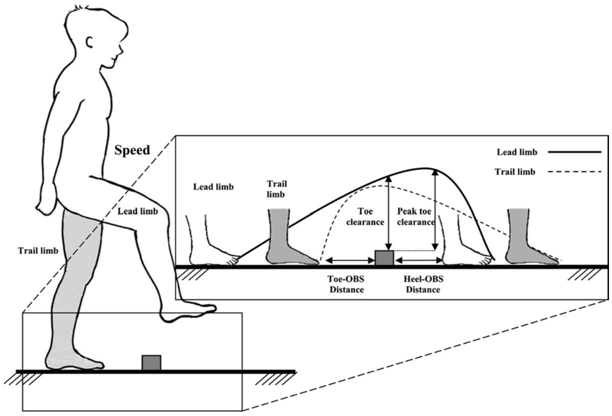

Fig. 1. The parameters derived from the kinematic data

crossing the obstacle.

The parameters derived from the kinematic data are defined in Fig. 1. Kinematic data were used to estimate the temporal-spatial parameters and limb end-point variables used in the analysis. The temporal-spatial parameters calculated were peak approach speed (AS) and crossing speed (CS). The following limb end-point variables were calculated: toe clearance (TC), heel clearance (HC), peak toe clearance (TC peak), peak heel clearance (HC peak), and step width (SW). With the exception of SW, all end-point variables were calculated for both the leading and the trailing limbs. Between-group differences (i.e., variability between the high- and low-risk groups) in temporal-spatial parameters and limb end-point variables were evaluated using a two-way analysis of variance (ANOVA) with repeated measures of obstacle height. Differences between the leading and trailing limbs were compared using a paired-t test. The symmetry ratio, which provides a comparison of the clearance profile for both legs, was developed to provide a simple method of screening for risk of trips and falls over obstacles in clinical practice. The symmetry index was calculated as follows:

$$\text{Symmetry ratio} = \frac{\text{clearance}_{\text{lead}} - \text{clearance}_{\text{trail}}}{(\text{clearance}_{\text{lead}} + \text{clearance}_{\text{trail}})*0.5} \quad \text{Equation (1)}$$

Specifically, the symmetry index provides an estimate of the difference in clearance height for the leading and the trailing limbs. A ratio of '0' indicates symmetrical clearance for both limbs, a positive ratio indicates greater clearance of the leading foot, and a negative ratio indicates greater clearance of the trailing foot.

RESULTS

All participants reduced their gait speed while crossing the obstacle compared to the walking speed during the approach phase (Table 2). Between-group differences were identified for step width, as well as toe and heel clearance for the leading leg ($p<0.05$). In particular, the low-risk group showed lower clearance of the toe and higher clearance of the heel, compared to the high-risk group; additionally, the higher risk group adopted a narrower step width than the low-risk group ($p<0.05$). Moreover, the low-risk group had a tendency to have a lower symmetry index (Table 3).

Obstacle height significantly modulated the swing duration of the leg crossing the obstacle. After normalizing swing phase to total stride duration, the swing phase of the leading leg increased as a function of obstacle height. Limb clearance parameters were also modulated by obstacle height, including increases in both peak heel clearance and toe clearance of the leading and trailing limbs. Even after normalization of the data for leg length, differences in the peak clearance height for the different obstacle heights remained significant ($p<0.05$). Therefore, with increasing obstacle height, older adults tended to lift their foot higher to clear the top of the obstacle, requiring more time (i.e., a longer swing phase) to clear the higher obstacle, independent of high- or low-risk group assignation.

Group × obstacle height interaction produced a discrete effect on the toe clearance of the leading limb ($p<0.05$). Effects of obstacle height on the kinematics of the crossing leg are listed in Table 4. When crossing an obstacle height adjusted to 10% of leg length, heel clearance, peak heel clearance, toe clearance, and peak toe clearance of the leading limb were all lower than for the trailing limb ($p<0.05$). When obstacle height increased to 20% of leg length, between-limb asymmetries emerged, with decreased crossing speed, heel clearance, peak heel clearance, and peak toe clearance for the leading limb as compared to the trailing limb ($p<0.05$).

Table 2. Temporal-distance gait measurements for the high- and low-risk group while crossing over obstacles heights of 10%, 20%, and 30% of subjects' leg length

Group	Obstacle height					
	10%		20%		30%	
	High risk	Low risk	High risk	Low risk	High risk	Low risk
Step length (cm)	53.9 ± 3.3	54.1 ± 4.4	54.2 ± 3.0	55.0 ± 5.3	54.9 ± 2.3	52.9 ± 4.2
Step width (cm) *	5.3 ± 2.3	8.1 ± 2. 5	6.2 ± 2.7	9.5 ± 3.7	5.5 ± 3.2	8.0 ± 3.6
Swing time $_{lead}$ (%) †	51.0 ± 3.5	51.7 ± 4.4	53.5 ± 2.6	53.5 ± 4.5	56.5 ± 3.6	56.1 ± 4.3
Swing time $_{trail}$ (%)	44.4 ± 5.1	42.8 ± 2.4	43.3 ± 2.4	43.8 ± 2.8	42.0 ± 3.7	44.3 ± 3.4
Crossing speed $_{lead}$ (cm/s)	65.0 ± 11.7	59.3 ± 11.5	56.4 ± 9.9	57.1 ± 13.5	46.3 ± 10.6	51.1 ± 13.5
Crossing speed $_{trail}$ (cm/s)	63.7 ± 12.7	59.2 ± 11.8	59.7 ± 9.9	60.1 ± 15.2	53.5 ± 8.9	56.1 ± 14.7
Peak approach speed (cm/s)	102.3 ± 16.0	102.8 ± 14.1	104.0 ± 14.3	108.5 ± 13.3	103.0 ± 12.6	109.1 ± 12.7
Heel clearance $_{lead}$ (cm)	10.1 ± 3.2	13.1 ± 2.5	10.3 ± 3.1	13.6 ± 3.1	8.1 ± 3.1	11.5 ± 3.3
Heel clearance $_{trail}$ (cm)	33.6 ± 5.0	32.2 ± 3.0	34.4 ± 6.3	32.4 ± 4.4	31.1 ± 6.9	29.5 ± 4.9
Peak heel clearance $_{lead}$ (cm) †	35.9 ± 5.3	36.2 ± 3.4	42.4 ± 5.6	42.8 ± 3.6	48.6 ± 6.3	49.3 ± 4.2
Peak heel clearance $_{trail}$ (cm) †	45.0 ± 5.6	43.7 ± 2.4	52.8 ± 6.6	51.0 ± 2.9	60.8 ± 6.3	61.0 ± 3.7
Toe clearance $_{lead}$ (cm) *‡	17.2 ± 4.3	15.0 ± 2.8	17.4 ± 5.5	15.7 ± 3.9	15.2 ± 5.4	14.0 ± 3.9
Toe clearance $_{trail}$ (cm)	14.1 ± 3.6	14.8 ± 2.0	14.1 ± 2.8	14.0 ± 2.0	11.7 ± 2.9	16.1 ± 3.4
Peak toe clearance $_{lead}$ (cm) †	25.6 ± 4.3	25.9 ± 2.3	32.9 ± 3.4	33.5 ± 2.2	40.2 ± 3.6	42.0 ± 3.5
Peak toe clearance $_{trail}$ (cm) †	28.8 ± 5.0	26.0 ± 2.3	35.9 ± 6.1	33.2 ± 2.5	43.3 ± 6.0	43.1 ± 3.3
Toe-obs distance $_{trail}$ (cm) †	20.7 ± 3.6	18.8 ± 2.3	19.4 ± 4.3	19.7 ± 2.5	23.1 ± 4.8	23.0 ± 2.2
Heel-obs distance $_{lead}$ (cm)	12.6 ± 2.9	12.5 ± 3.5	15.0 ± 4.0	12.6 ± 2.8	14.8 ± 3.3	13.5 ± 3.7

*p-values (<0.05) for the high/low risk between-group analysis of variance (ANOVA) for all obstacle heights.
†p-values (<0.05) for the OBS height ANOVA for all groups.
‡p-values (<0.05) for the OBS height × groups two-way ANOVA

Table 3. The symmetry ratio of foot clearance for both groups while crossing an obstacle height corresponding to 10% of subjects' leg length

Group	High risk	Low risk
Heel clearance *	−1.1 ± 0.2	−0.9 ± 0.2
Peak heel clearance*	−0.2 ± 0.1	−0.2 ± 0.1
Toe clearance *	−0.2 ± 0.2	0.0 ± 0.2
Peak toe clearance *	−0.1 ± 0.1	0.0 ± 0.1

*p-values (<0.05) for the between-group variables; student t-test.

Table 4. Temporal-distance gait measurements for the leading and trailing leg while crossing over obstacles heights of 10%, 20%, and 30% of subjects' leg length

Crossing limb	Obstacle height					
	10%		20%		30%	
	Lead	Trail	Lead	Trail	Lead	Trail
Crossing speed †‡	61.2 ± 12.0	61.0 ± 12.7	55.3 ± 10.8	58.7 ± 12.3	47.5 ± 11.8	53.6 ± 11.9
Step length	105.5 ± 7.5	106.6 ± 9.2	106.0 ± 9.5	106.2 ± 9.8	105.0 ± 8.7	107.1 ± 8.0
Heel clearance *†‡	11.7 ± 3.0	32.9 ± 4.4	11.4 ± 2.9	32.1 ± 5.6	11.5 ± 3.7	31.5 ± 5.6
Peak heel clearance *†‡	36.3 ± 4.5	44.7 ± 4.4	43.5 ± 4.6	52.7 ± 5.0	48.6 ± 5.2	60.5 ± 5.3
Toe clearance *	14.5 ± 3.1	16.2 ± 3.9	14.2 ± 2.6	15.8 ± 5.1	14.0 ± 3.1	15.8 ± 4.5
Peak toe clearance *‡	25.9 ± 3.5	27.6 ± 4.2	33.7 ± 3.0	35.3 ± 5.1	41.1 ± 3.1	43.0 ± 4.8

*p-values (<0.05) for the variables of leading and trailing leg while negotiating an obstacle height adjusted to 10% of leg length; paired sample t-test.
†p-values (<0.05) for the variables of leading and trailing leg while negotiating an obstacle height adjusted to 20% of leg length, paired sample t-test.
‡p-values (<0.05) for the variables of leading and trailing leg while negotiating an obstacle height adjusted to 30% of leg length, paired sample t-test.

DISCUSSION

The body of research regarding the risk of falling in older adults has expanded considerably over the past decade, with a focus on understanding age-related changes in balance and gait while negotiating obstacles. A shared limitation of this research, however, can be seen in the selection bias of older adults recruited solely from among university staff, clinical research centers, or institutions. A novel aspect of our study is our random selection of community-dwelling older adults, including a direct comparison of the performance of individuals at high-risk of falling to the performance of healthy, age-matched controls. In addition, risk of falling was screened using the Tinetti component of the POMA test, which has been shown to have marked sensitivity in detecting minor impairments in gait and balance functionality in older adults and predictive reliability for falls and fall-related injuries in community-dwelling older adults[8, 15, 32)].

Our study focused specifically on lower limb kinematics while crossing obstacles of different heights, and compared the profiles of older adults at either high or low risk of falling. Previous studies reported that the individuals generally chose their dominant foot as the leading foot and that this selection bias increased while negotiating higher obstacles[18, 33)]. We observed a similar leading limb selection bias in our study. Our outcomes also indicated that older adults used a more conservative strategy to negotiate obstacles, compared to young adults, including a slower crossing speed, increased crossing time, and higher foot clearance while crossing over the obstacles. Previous studies[18, 34–40)] also reported that older adults adopted a slower and shorter step length, more conservative strategy that provides older adults with more time to adjust their limbs in order to reduce the risk of tripping. A similar finding was reported in individuals with gait and balance issues, while individuals with Parkinson's disease demonstrated shorter stride length and greater stride duration[31, 41)]. However, Muir et al. considered this strategy to be detrimental for obstacle crossing due to the increased risk of inappropriate limb contact[42)].

Overall, minimal toe clearance and greater variability of foot clearance may increase the risk of trips and associated falls[43, 44)] and we found that the high-risk group had more variability in toe and heel clearance. However, because the chosen point of reference on the foot, heel or toe may vary in location, relevant comparisons of kinematic measurements between studies are limited. Chen et al. reported similar heights of heel and toe clearance of the leading foot for healthy young and older adults stepping over an obstacle of fixed height, with the sole of the leading foot appearing virtually horizontal as it crossed the obstacle and the heel at the lowest height in 82% of trial[18)]. Sparrow et al. reported a modulation in the clearance height of the heel of the leading limb by the height of the obstacle, with a lower clearance height used when negotiating lower obstacles, compared to obstacles of medium and high heights[33)]. In our study, the lowest point of clearance for the leading limb was at the level of the heel and toe of the trailing limb. The absence of obstacle height standardization further limits comparison of outcomes between studies. To address this specific issue, we adjusted the height of the obstacles to a percentage of leg length for each participant, with the 10–30% height proportions used corresponding to a range of heights that are navigated in activities of daily living, from the threshold of a door (5 cm) to the height of the standard step (25 cm).

Previous studies reported that as obstacle heights increased, older adults modified their strategy to decrease crossing speed, increase toe and heel clearance, and increase the crossing time of the leading limb[18, 33, 45)]. In our study, we revealed that as the obstacle height increased, a longer swing time of the leading leg was required for the crossing procedure, accompanied by significantly higher peak clearance for both the leading and trailing limbs. Interestingly, older adults at high-risk of falling used much greater toe clearance than those with a low risk of falling. We further demonstrated the peak heel clearance of the trailing limb to be greater than that of the leading limb in individuals with a low risk of falling. In contrast, individuals at high risk of falling adopted a narrower step width and greater toe clearance of the leading limb. A similar finding was reported by Chen et al. who observed greater toe clearance in healthy elderly male subjects negotiating obstacles when compared to young male subjects[18)]. They also concluded that improved gait ability reduced the risk of falls for the older adults. Recently published studies reported that exercise could help to improve the strategies (increased toe clearance, heel clearance and maximum vertical heel clearance) used by the older adults to negotiate obstacles[46, 47)].

Older adults at high risk for falls generally have an asymmetry in foot clearance[48)]. According to our findings, individuals in the high-risk group showed significantly asymmetrical foot lift while crossing obstacles of height adjusted to 10% of their leg length. Moreover, they had a greater asymmetry of the foot lift ratio, using a higher foot clearance of the trailing leg compared to the leading leg. Additional research is needed to determine whether the mechanism causing these differences might influence balance function and, thereby, the risk of falling when negotiating obstacles.

In our view, the results of our study have important clinical implications for physical therapists and nursing staff. A leading cause of falls in older individuals is tripping while negotiating obstacles. Understanding the characteristics of the adaptive strategies used for obstacle negotiation provides a basis for implementing relevant reeducation protocols to improve performance. Key parameters of such a program should include increasing step width and normalizing the symmetry index.

The limitations of our study should be noted when evaluating the applicability of our findings to clinical practice. Our analysis is based on the findings from a small study group whose participants were all able to walk independently in their community without physical aid or assistance. Future studies with a larger sample size would allow further analysis and provide insight into specific deficits in the performance of obstacle crossing which could be predictive of falls both at home and in the community.

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