

# Comparisons of the lower limb kinematics between young and older adults when crossing obstacles of different heights

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## Abstract

Fifteen young and 15 older healthy adults walked and crossed obstacles with heights of 10%, 20% and 30% of their leg lengths while their kinematic data were measured with a three-dimensional (3D) motion analysis system. End-point variables together with 3D joint kinematics of both the leading and trailing limbs were obtained. The results showed that the older group adopted a swing hip flexion strategy to achieve a higher leading toe clearance than the young group. With increasing obstacle height, the older group increased linearly the leading toe clearance by changing fewer joint angular components than the young group, allowing the maintenance of the necessary stability of the body with minimum control effort. When the trailing limb was crossing, the older group showed no significant difference in the trailing toe clearance compared to the young group, although different joint kinematic patterns were evident. The older group seemed to use a more conservative strategy for obstacle-crossing. Failure to implement this strategy during obstacle negotiation may increase the risk of falls owing to an inability to recover from unexpected tripping or stumbling. The results of this study suggest that existing knowledge of the kinematic control of obstacle-crossing based on young subjects may serve as a baseline for further studies on older people for a better understanding of the mechanisms and for the prevention of falls in the elderly.

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## 1. Introduction

Tripping over obstacles during locomotion has been reported as one of the most frequent causes of falls [1–5], research on the kinematics and kinetics of the lower extremities during this functional activity and has received much attention [6–18]. Knowledge of the mechanics of the locomotor system during obstacle-crossing is helpful for the design of fall-prevention devices and for the planning of programs for the prevention of associated injuries.

Results of previous studies on young adults have formed the foundation of the current knowledge on the mechanics and control of the lower extremities during obstacle-crossing, mainly through kinematic and kinetic analyses of the leading and trailing limbs when crossing obstacles of different heights [6–12,14–16,18]. Emphasis has been on the

descriptions of the foot trajectory during obstacle negotiation, a precise end-point control task, using variables such as foot clearance and foot-obstacle horizontal distances, as well as the intersegmental coordination that determines the end-point trajectory, using joint crossing angles and joint moments. Data on the end-point variables in combination with the intersegmental coordination patterns are helpful for the investigation of the strategies that might be employed in obstacle-crossing. In general, in healthy young adults higher muscular demand on the stance limbs was needed for crossing higher obstacles as revealed by the peak joint moments [12,15]. With a stable supporting limb, young adults maintained horizontal distances of both the trailing limb (toe-obstacle distance) and leading limb (heel-obstacle distance) that were not affected by obstacle height [11,16,18]. Some studies reported that young adults also maintain relatively constant foot clearance mainly by increasing angular motions of the joints of the swing limb [11,12]. However, other studies contradict this and have

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suggested that foot clearance might be affected by obstacle height [9,11,16]. This controversy may be explained by the influence of inter-subject anthropometric differences; therefore, it has been suggested that obstacles should be adjusted for each subject according to their leg length [11,14]. A recent kinematic study on young adults crossing leg-length-normalized obstacles found that both leading and trailing foot clearance remained relatively constant with increased obstacle height and that these clearances were not significantly different in magnitude between limbs [18]. Knowledge of the mechanics and control of the lower extremities during obstacle-crossing has been established through extensive research on young adults crossing obstacles of different heights. However, since aging can cause muscle weakness, degradation of balance control and insufficient coordination that may affect the performance of locomotion and obstacle negotiation, the ability to recover from an unexpected trip may also be greatly affected. Whether or not the bulk of the existing knowledge based on young subjects can be applied directly to the elderly remains to be answered.

There have been a number of recent studies devoted to uncovering possible age-related factors, which may influence locomotion during obstacle-crossing (e.g. [19–24]). Lamoureux et al. [21] studied the relationship between lower limb muscle strength and the obstructed gait in older adults and found a significant correlation. In a later study they suggested that improving muscle strength could improve the crossing strategy characterized by increased stride velocity, heel clearance and limb flexion [22]. Chou et al. [23] studied the motion of the center of mass (COM) of the elderly during obstacle-crossing and suggested that medio–lateral motion of the COM can be used to distinguish the elderly with imbalance from the normal. Schrodt et al. [24] suggested that the elderly place higher emphasis on gait performance during obstacle-crossing when combined with a cognitive task. None of these studies investigated the height effect on the lower limb kinematics in older adults. Further, only the older group was studied, without a comparison with a younger control group.

A limited number of previous studies that compared performances of the older adults with those of young ones during obstacle-crossing showed that differences between the two age groups existed when facing surface type changes [17], postural threat [25] or different available response time [26,27], or when adopting different walking speeds [28]. Chen et al. [7] studied the obstacle height effects on foot clearance, crossing speed, horizontal distances, step length and step width between healthy older and young adults, but their obstacles were not normalized to the subjects' leg lengths. Hahn and Chou [29] reported the height effects on temporal–distance gait variables and the motion of the COM during obstacle-crossing in both groups. Neither Chen et al. [7] nor Hahn and Chou [29] provided data on the lower limb joint kinematics of both the leading and trailing limbs. It is noted that no study has investigated the age and height

effects on the end-point variables and joint kinematics of both the leading and trailing limbs by directly comparing older and young subjects under the same experimental protocol and analysis method. Therefore, the purpose of the present study was to investigate whether differences exist in the joint angles and end-point variables, namely horizontal distance, step length and toe clearance, between young and older groups when crossing obstacles adjusted at 10%, 20% and 30% of leg length. It is hoped that the results of the study will help identify potential risk factors for falls in the elderly.

## 2. Materials and methods

Fifteen young adults (mean age: 23 years, standard deviation: 3 years; mean height: 176.1 cm, standard deviation: 6.3 cm; mean mass: 68 kg, standard deviation: 8.6 kg) and 15 older adults (mean age: 72 years, standard deviation: 6 years; mean height: 160 cm, standard deviation: 5.7 cm; mean mass: 58 kg, standard deviation: 10.4 kg) participated in the present study with informed consent. They all had normal corrected vision and were free of pathology that might affect gait and/or cognitive function. Each subject walked at a self-selected pace on an 8-m walkway and crossed a height-adjustable obstacle that was composed of a 1.5 m long aluminum tube with a diameter of 1.5 cm placed across a metal frame. Two infrared retro-reflective markers were placed on each end of the tube to define the position of the obstacle. The tube was light and rigid so it would drop off the frame when contacted. The subjects were allowed to familiarize themselves with the walkway before experimental data were recorded. Twenty-eight markers were placed on specific anatomical landmarks on the pelvis (ASISs and PSISs) as well as each thigh (greater trochanter, mid-thigh, medial and later epicondyles), shank (head of fibula, tibial tuberosity, medial and lateral malleolus) and foot (navicular tuberosity, 5th metatarsal base, big toe and heel). Coordinates of these markers gathered during a static calibration trial were used to define anatomical coordinate systems of the segments. During dynamic trials, the medial epicondylar and malleolar markers were removed to prevent affecting limb movement. Kinematic data were measured using a 7-camera motion analysis system (Vicon 512, Oxford Metrics Group, UK) at a sampling rate of 120 Hz. Two forceplates (Advanced Mechanical Technology Inc., USA) were placed on each side of the obstacle to measure the ground reaction forces (GRF). Test conditions included crossing obstacles of three different heights (10%, 20% and 30% of leg length) for both limbs. For all conditions, subjects were instructed to walk along the walkway and step over the obstacle when necessary. Six trials, three for each leg, for each condition were recorded.

Marker data for each test condition were used to calculate joint crossing angles and end-point variables, namely foot-obstacle distances, step length and foot clearances. The

trailing foot-obstacle distance was defined as the shortest horizontal distance between the toe marker and the obstacle (toe-obstacle distance), and the leading foot-obstacle distance as the shortest horizontal distance between the heel marker and obstacle (heel-obstacle distance), following the literature (e.g. [7,16]). Step length was defined as the horizontal distance between both limbs along the direction of progression in the crossing step using the heel markers. Data of heel-obstacle distances, toe-obstacle distances and step lengths were normalized to leg lengths. Toe clearances of both limbs were calculated as the vertical distances between the toe markers and the obstacle when the toe was directly above the obstacle. Each body segment was embedded with an orthogonal coordinate system with the positive *x*-axis directed anteriorly, positive *y*-axis superiorly and positive *z*-axis to the right. A cardanic rotation sequence (*Z–X–Y*) was used to describe the rotational movements of each joint [30]. The angles for each joint of both the stance and swing limbs when the toe marker was directly above the obstacle (crossing angles) were calculated for further statistical analysis. Data on the crossing joint angles in combination with those of the toe clearances provided a basis for the study of the relationship between the intersegmental coordination and end-point control. The obstacle height effects on the calculated variables for each age group were tested using repeated measures analysis of variance (RMANOVA) with a polynomial test to determine the trend (linear and quadratic,  $\alpha = 0.05$ ) [31]. Comparisons between the two groups were made with independent *t*-tests for all height conditions ( $\alpha = 0.05$ ). SPSS version 10.0 (SPSS Inc., Chicago, IL) was used for all statistical analyses.

### 3. Results

Comparisons between the older and young groups revealed that the older group had shorter leading heel-obstacle distances and longer trailing toe-obstacle distances for all heights as well as higher leading toe clearances for the 20% and 30% conditions ( $p < 0.05$ ), Table 1 and Fig. 1(A).

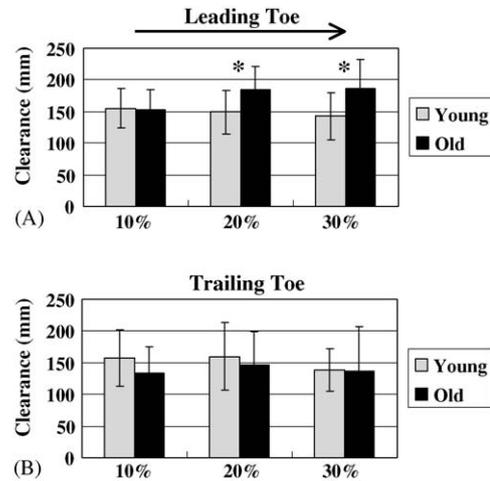


Fig. 1. Mean toe clearances of both the leading and trailing limbs for both age groups. Standard deviations are shown as error bars. An asterisk indicates a significant difference between the older and young groups. A right arrow above the graph indicates a linearly increasing trend with increasing obstacle height in the older group.

With increasing obstacle height, linearly increasing leading toe clearances ( $F(2, 28) = 9.20, p < 0.05$ ) and linearly decreasing heel-obstacle distances ( $F(2, 28) = 4.38, p < 0.05$ ) were found in the older group while linearly decreasing crossing step lengths were found in both age groups (older,  $F(2, 28) = 7.55, p < 0.05$ ; young,  $F(2, 28) = 3.77, p < 0.05$ ), Table 1. Trailing toe clearances for both groups were not affected by obstacle height ( $p > 0.05$ ) and no differences were found between the older and young groups for all heights ( $p > 0.05$ ), Fig. 1(B).

When the leading toe was above the obstacle, bigger hip crossing flexion and smaller ankle crossing eversion of the leading swing limb were found in the older group, as compared with the young group ( $p < 0.05$ ), Figs. 2–4. Greater hip crossing flexion, adduction and ankle crossing dorsiflexion of the trailing stance limb were also found in the older group for the 10% condition ( $p < 0.05$ ), Figs. 2–4. With increasing obstacle height the older group adopted linearly increased crossing flexion of all the leading

Table 1  
End-point variables for the young and older groups when crossing obstacles of three different heights (10%, 20% and 30% leg length)

End-point variables	Height effect	Age effect						
		Older		Young				
		Mean	S.D.	Mean	S.D.			
Leading heel-obstacle distance (% leg length)	10%	18.40	(5.14)	↓	20.40	(3.78)	–	Y > O
	20%	16.38	(3.68)		20.30	(3.71)		Y > O
	30%	15.09	(4.51)		19.29	(3.40)		Y > O
Trailing toe-obstacle distance (% leg length)	10%	24.94	(4.42)	–	20.94	(2.56)	–	O > Y
	20%	24.60	(4.15)		20.39	(2.38)		O > Y
	30%	24.24	(4.76)		20.63	(2.70)		O > Y
Step length (% leg length)	10%	72.04	(5.94)	↓	69.89	(4.54)	↓	–
	20%	69.65	(4.01)		69.26	(4.61)		–
	30%	67.88	(4.83)		68.38	(4.51)		–

With increasing obstacle heights, ↑ indicates a linearly increasing trend; ↓ linearly decreasing trend and – no effect (O: older group, Y: young group).

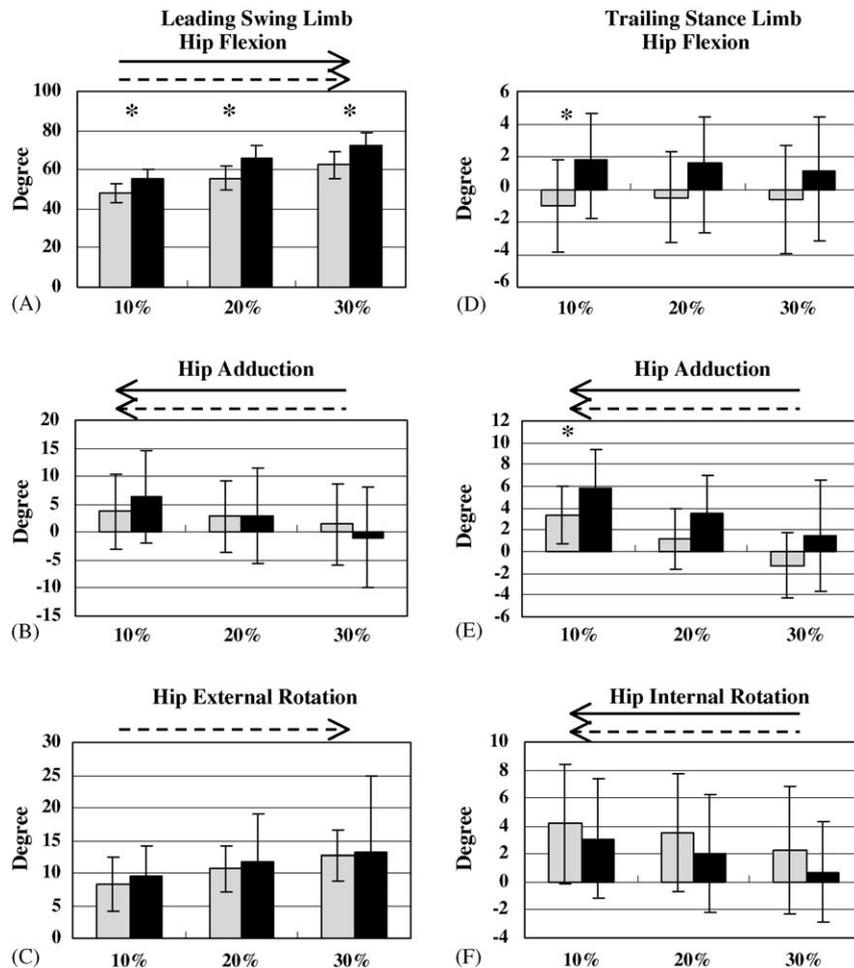


Fig. 2. Mean hip crossing angles of both limbs when the leading toe is above the obstacle. An asterisk indicates a significant difference between the older and young groups. With increasing obstacle height, a right arrow above the graph indicates a linearly increasing trend while a left arrow indicates a linearly decreasing trend (black bar/solid arrow: the older group; grey bar/dashed arrow: the young group).

swing joints (hip,  $F(2, 28) = 121.30$ ,  $p < 0.05$ ; knee,  $F(2, 28) = 131.28$ ,  $p < 0.05$ ; ankle,  $F(2, 28) = 16.13$ ,  $p < 0.05$ ) and linearly reduced leading hip crossing adduction ( $F(2, 28) = 44.27$ ,  $p < 0.05$ ) and knee crossing abduction ( $F(2, 28) = 26.56$ ,  $p < 0.05$ ) while the other joint angular components remained independent of obstacle height, Figs. 2–4. The same results were also found in the young group except that the leading hip and knee crossing external rotations were also increased linearly with obstacle height (hip,  $F(2, 28) = 26.54$ ,  $p < 0.05$ ; knee,  $F(2, 28) = 9.00$ ,  $p < 0.05$ ), Figs. 2–4. At the same time, both age groups decreased linearly hip crossing adduction (older,  $F(2, 28) = 11.97$ ,  $p < 0.05$ ; young,  $F(2, 28) = 88.35$ ,  $p < 0.05$ ), internal rotation (older,  $F(2, 28) = 14.05$ ,  $p < 0.05$ ; young,  $F(2, 28) = 8.22$ ,  $p < 0.05$ ) and ankle crossing dorsiflexion (older,  $F(2, 28) = 15.05$ ,  $p < 0.05$ ; young,  $F(2, 28) = 11.68$ ,  $p < 0.05$ ) of the trailing stance limb, Figs. 2–4. The other joint angular components remained constant in the older group ( $p > 0.05$ ) but the trailing knee crossing flexion and abduction were linearly increased in the young group (flexion,  $F(2, 28) = 11.55$ ,  $p < 0.05$ ; abduction,  $F(2, 28) = 17.86$ ,  $p < 0.05$ ), Figs. 2–4.

When the trailing toe was above the obstacle, the older group had bigger hip crossing flexion in the trailing limb for all heights as well as bigger hip flexion and adduction in the leading stance limb for the 10% condition than the young group ( $p < 0.05$ ), Tables 2 and 3. Although statistical significances were not found in the leading hip flexion and adduction for the 20% and 30% conditions, there were trends that the older group had higher values in these two components. With increasing obstacle height, effects on the joint kinematics were largely the same for both groups. Similar trends between the older and young groups also existed in the hip adduction and knee external rotation of the trailing swing limb, as well as knee abduction and internal rotation of the leading stance limb, although these were not statistically significant, Tables 2 and 3.

#### 4. Discussion

The aim of the present study was to investigate the differences of the end-point trajectory and the joint kinematic patterns between the older and young groups in

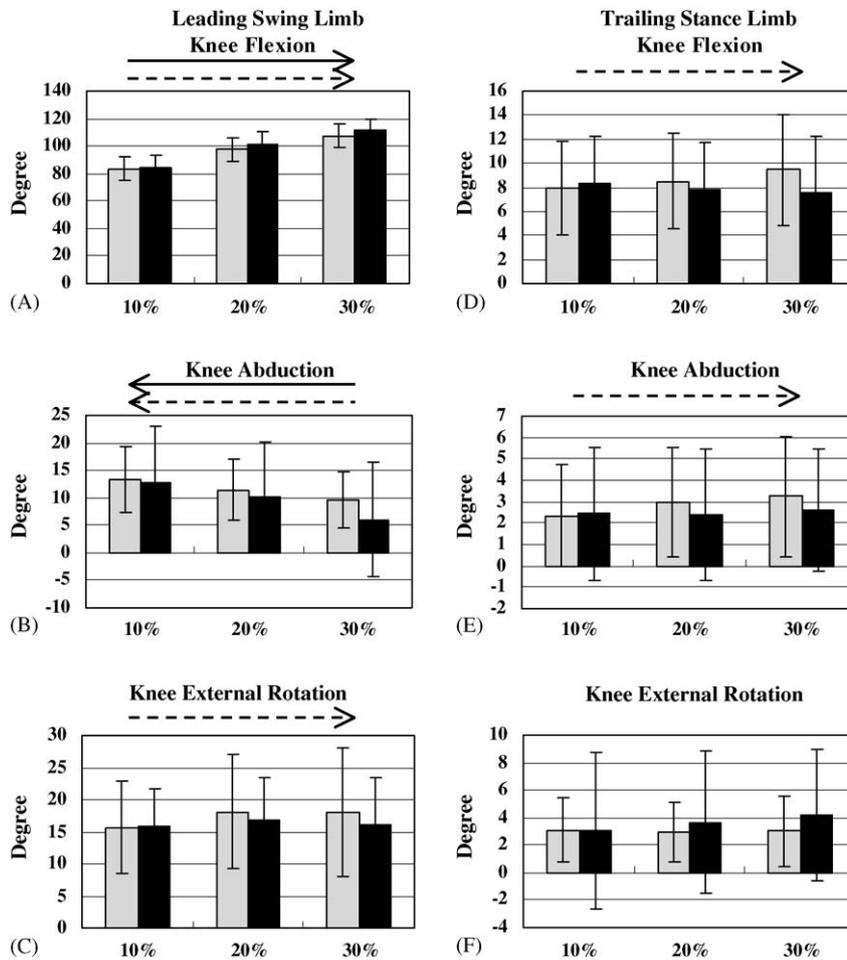


Fig. 3. Mean knee crossing angles of both limbs when the leading toe is above the obstacle. An asterisk indicates a significant difference between the older and young groups. With increasing obstacle height, a right arrow above the graph indicates a linearly increasing trend while a left arrow indicates a linearly decreasing trend (black bar/solid arrow: the older group; grey bar/dashed arrow: the young group).

terms of the end-point variables and the joint angles when crossing obstacles of different heights, in the hope of revealing age-related changes in the crossing strategy.

Compared to the young, the older subjects increased their leading toe clearance to achieve safer crossing with reduced risk of tripping (toe-obstacle contact), Fig. 1(A). This suggests that greater challenges were perceived by the older group when crossing obstacles of 20% and 30% leg length. Similar results on clearances were also found by Watanabe and Miyakawa [34] and Patla et al. [32] (cited in McFadyen and Prince, [17]). However, McFadyen and Prince [17] found that the older subjects had smaller toe clearance than the young group when crossing a 117.5 mm obstacle (between 10% and 20% conditions in the present study). Although higher clearance in the older group resulted in shorter leading heel-obstacle distance (Table 1), and which may indicate a higher risk of stumbling (heel-obstacle contact) than for the young group, this strategy is beneficial as heel or midsole contact may carry less risk for a fall than does toe contact, as suggested by Chen et al. [7].

The difference in the leading end-point control strategy between the two age groups was also indicated by the

different height effects on the leading toe clearance and leading heel-obstacle distance, Table 1 and Fig. 1(A). The young group maintained relatively constant leading toe clearance and leading heel-obstacle distance regardless of obstacle height, while the older group had to increase linearly the former and reduced linearly the latter with increased obstacle height. This height dependent end-point trajectory in the older group suggests that a higher safety factor was set, most likely in order to compensate for the reduction in the ability to recover from unexpected tripping owing to age-related physical degradation. Increased leading toe clearance would require increased muscular demands on the swing limb. If these demands were not met, such as a result of age-related muscle weakness, the older people would not be able to recover from tripping over the obstacle and the risk of falls would also increase.

There was no significant difference in the control of the trailing end-point between the two age groups. Why the older group did not increase the trailing toe clearance as it did for the leading limb can be explained by the greater variability of the trailing toe clearance found in the present study. Unlike for the leading limb, visual cues were

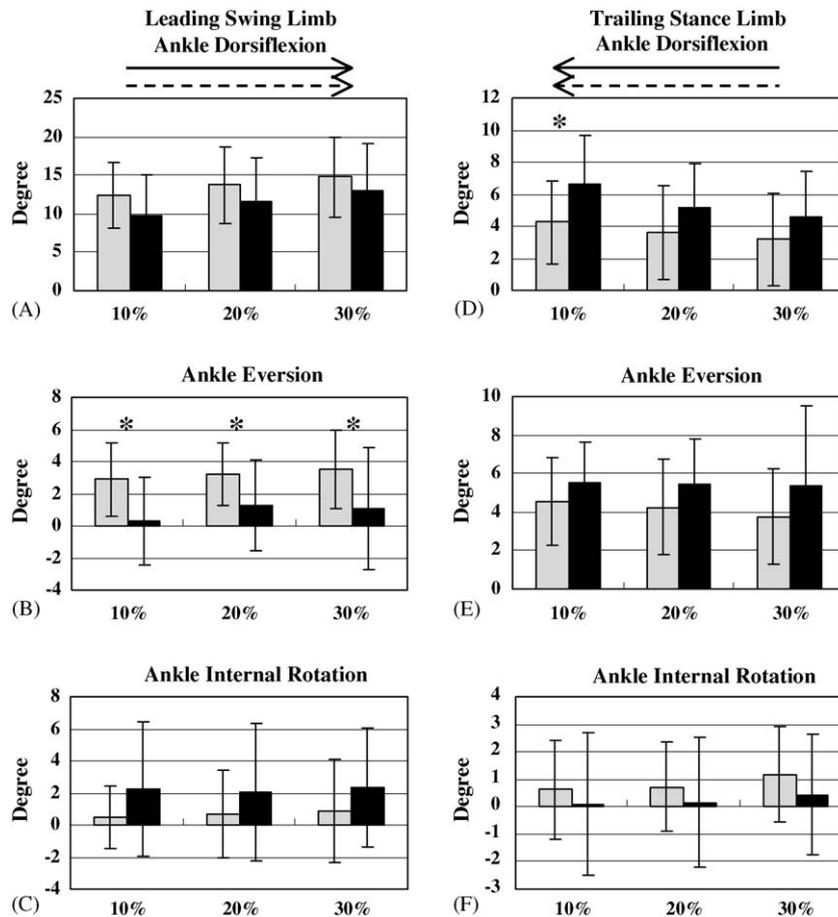


Fig. 4. Mean ankle crossing angles of both limbs when the leading toe is above the obstacle. An asterisk indicates a significant difference between the older and young groups. With increasing obstacle height, a right arrow above the graph indicates a linearly increasing trend while a left arrow indicates a linearly decreasing trend (black bar/solid arrow: the older group; grey bar/dashed arrow: the young group).

unavailable when the trailing limb was crossing, contributing to the variability of the control of the toe trajectory [32,33]. This may not necessarily increase the risk of falls in the older group because mechanical demands on the trailing and leading limbs were different when they were supporting the body for the ipsilateral limb to cross. When the leading limb was crossing and the trailing limb was supporting the body, the COM was moving away from the base of support (the trailing foot), making the recovery of balance from tripping or stumbling more difficult. On the other hand, when the trailing limb was crossing, the COM was moving towards the leading stance foot, reducing the likelihood of instability of the stance limb. Therefore, recovery from tripping or stumbling caused by the trailing limb may be easier than when caused by the leading limb.

The precise control of the end-point of the lower limb is a result of well-coordinated movements of the limb segments described by the joint kinematics. Most previous studies investigating obstacle-crossing focused only on the joint angles of the swing limb (e.g. [7–9,11–13,16]). However, since the joint kinematics of both the stance and swing limb contribute to the control of the swing toe, a better understanding of the lower limb end-point control should

consider the joint kinematics of both the swing and stance limbs.

When the leading toe was above the obstacle, the older group used a swing hip flexion strategy to achieve desired foot clearance while the young group adopted a swing ankle eversion strategy for all heights, Figs. 2–4. To accommodate these changes in the swing limb, the older group used bigger hip crossing flexion, adduction and ankle crossing dorsiflexion of the trailing stance limb than the young group in the 10% condition, Figs. 2–4. The flexed position of the trailing stance limb adopted by the elderly tended to lower the position of the leading toe and to offer more stable support while the bigger crossing flexion at the leading hip helped increase the upward position of the leading toe. These two different limb positional strategies resulted in unchanged leading toe clearance between both age groups in the 10% condition. For higher obstacles, although both groups adopted the same crossing angular displacements of the trailing stance limb, older subjects flexed their leading hips more to achieve higher toe clearance. The hip, the most proximal joint of the lower limb, offered a more efficient means of elevating the swing toe than the ankle for the older group. However, it required greater hip flexor forces to elevate

Table 2  
Height and age effects on the crossing angles of the joints of the swing limb when the trailing toe was above the obstacle

Crossing angle (°)	Group	Obstacle height						Height effect	Age effect	
		10%		20%		30%				
		Mean	S.D.	Mean	S.D.	Mean	S.D.			
<b>Hip</b>										
Flex	Y	19.46	(5.27)	23.62	(5.62)	26.90	(5.79)	↑	O > Y (All conditions)	
	O	24.48	(6.03)	29.98	(5.73)	33.92	(6.01)	↑		
Add	Y	1.02	(4.97)	1.93	(5.76)	2.75	(6.18)	↑		–
	O	3.47	(3.81)	4.43	(5.74)	4.03	(6.88)	–		–
IR	Y	0.36	(4.69)	0.39	(4.04)	0.38	(4.03)	–		–
	O	2.85	(4.94)	2.43	(5.62)	2.39	(6.40)	–		–
<b>Knee</b>										
Flex	Y	91.93	(14.51)	108.96	(8.58)	118.88	(8.01)	↑	–	
	O	95.95	(8.77)	112.51	(8.96)	124.60	(7.63)	↑	–	
Abd	Y	15.41	(6.14)	15.16	(5.31)	12.77	(4.71)	↓	–	
	O	15.15	(9.67)	13.60	(10.34)	12.40	(9.27)	↓	–	
ER	Y	20.31	(8.78)	24.85	(10.14)	26.03	(10.60)	↑	–	
	O	21.48	(6.67)	22.72	(8.84)	23.37	(10.49)	–	–	
<b>Ankle</b>										
Dorsi	Y	1.90	(8.29)	4.84	(7.18)	7.78	(6.96)	↑	–	
	O	2.46	(7.47)	7.02	(9.02)	10.79	(7.83)	↑	–	
Eve	Y	3.39	(4.49)	3.81	(3.98)	4.20	(4.00)	–	–	
	O	2.01	(2.79)	2.32	(3.59)	2.51	(3.29)	–	–	
ER	Y	0.54	(2.68)	0.66	(2.49)	1.00	(2.28)	–	–	
	O	0.37	(3.19)	0.82	(5.67)	–0.43	(4.23)	–	–	

With increasing obstacle heights, ↑ indicates a linearly increasing trend, ↓ linearly decreasing trend and – no effect (O: older group, Y: young group).

Table 3  
Height and age effects on the crossing angles of the joints of the stance limb when the trailing toe was above the obstacle

Crossing angle (°)	Group	Obstacle height						Height effect	Age effect
		10%		20%		30%			
		Mean	S.D.	Mean	S.D.	Mean	S.D.		
<b>Hip</b>									
Flex	Y	8.20	(3.59)	8.11	(3.69)	8.25	(3.87)	–	O > Y (10%)
	O	11.41	(4.08)	10.35	(4.01)	10.94	(4.64)	–	
Add	Y	7.53	(2.54)	5.49	(2.98)	2.84	(3.21)	↓	O > Y (10%)
	O	10.69	(4.03)	8.15	(4.23)	3.99	(5.34)	↓	
ER	Y	–0.36	(4.09)	0.99	(3.76)	2.23	(4.38)	↑	–
	O	–0.61	(4.24)	0.74	(3.75)	3.21	(3.98)	↑	–
<b>Knee</b>									
Flex	Y	10.02	(5.95)	8.90	(5.91)	7.66	(5.74)	↓	–
	O	10.43	(5.26)	7.80	(4.24)	6.77	(3.66)	↓	–
Abd	Y	2.51	(2.87)	2.22	(2.74)	2.06	(2.80)	–	–
	O	2.61	(3.23)	1.99	(2.84)	1.57	(2.98)	↓	–
IR	Y	0.84	(2.38)	1.44	(2.58)	2.06	(2.55)	↑	–
	O	0.14	(4.58)	1.04	(4.64)	1.17	(5.39)	–	–
<b>Ankle</b>									
Dorsi	Y	2.87	(4.07)	3.02	(3.58)	3.26	(3.55)	–	–
	O	3.99	(2.96)	3.79	(3.27)	2.93	(4.45)	–	–
Eve	Y	3.00	(2.19)	2.52	(2.22)	2.69	(3.07)	–	–
	O	4.50	(2.20)	4.25	(2.98)	4.29	(2.77)	–	–
IR	Y	0.85	(2.06)	1.49	(2.08)	1.66	(2.37)	–	–
	O	0.14	(2.42)	0.82	(2.84)	0.59	(3.14)	–	–

With increasing obstacle heights, ↑ indicates a linearly increasing trend, ↓ linearly decreasing trend and – no effect (O: older group, Y: young group).

the whole limb. Inability to increase hip flexion due to insufficient flexor strength may imply a higher risk of falling.

Differences between the two age groups also existed in the adopted joint kinematic strategies for crossing obstacles of different heights with the leading limb, Figs. 2–4. The young group changed their swing joint kinematics for crossing obstacles of increasing heights with increased crossing flexion of all the joints, in agreement with previous 2D [8–10,13] studies. They also increased transverse plane crossing angles linearly and decreased frontal plane ones at the hip and knee, as found by Chen et al. [18]. Height effects on the stance joint kinematics in the present study also agreed with the literature [18]. These changes allowed the young group to maintain a constant toe clearance with increased obstacle height. The same joint kinematic changes were also found in the older group, except that the older group chose to keep unchanged the crossing external rotation of the leading hip and knee, as well as the crossing flexion and internal rotation of the trailing stance knee, Figs. 2–4. The older group changed fewer joint angular components than did the young group to negotiate obstacles of increasing heights. This approach may be helpful for the elderly to maintain the necessary stability of the body with minimum control effort, especially when age-related degradation of coordination is present.

When the trailing limb was crossing, the lower limb joint kinematics were quite different from when the leading limb was crossing, mainly because of the loss of visual cues and different limb position requirements. When the trailing toe was above the obstacle, the major differences in joint kinematics between the two groups were that the older group adopted bigger flexion of the trailing hip for all heights and tended to flex and adduct their leading hips more, Tables 2 and 3. From the point of view of end-point control, the flexion of both hips would contribute to a decrease in the toe clearance, but the trailing toe clearances of the older group were in fact not different from those of the young. It is postulated that the increases in the hip flexion in the older group were not for the control of the trailing toe trajectory, but for the anterior movement of the upper body to draw the body COM closer to the base of support (the leading stance foot), which would help maintain the stability of the body. Further study is needed to confirm this argument. The differences in the joint kinematic patterns between the two groups remained almost unchanged for different obstacle heights. The two groups adopted similar joint kinematic changes with unchanging trailing toe clearances to cross obstacles of increasing heights.

Different joint kinematic patterns were adopted by different age groups to achieve end-point controls that were most suitable for their physical conditions. It seems that the older group used a more conservative strategy for obstacle-crossing as a result of age-related physical degradation. Failure to implement this strategy during obstacle negotiation may increase the risk of falls owing to an inability to recover from unexpected tripping or stumbling.

## 5. Conclusions

Effects of age and obstacle height on the control of end-point trajectories and the associated intersegmental kinematics were studied. The older group adopted a swing hip flexion strategy to achieve a higher leading toe clearance than the young group, presumably for safety reasons. With increasing obstacle height, the older group increased the leading toe clearance by changing fewer joint angular components than the young group, allowing the maintenance of the necessary stability of the body with minimum control effort. When the trailing limb was crossing, the older group showed no significant difference in the trailing toe clearance compared to the young group, although there were differences in the joint kinematic patterns. It seems that the older group used a more conservative strategy for obstacle-crossing as a result of age-related physical degradation. Failure to implement this strategy during obstacle negotiation may increase the risk of falls owing to the inability to recover from unexpected tripping or stumbling. The results of this study suggest that existing knowledge of the kinematic control of obstacle-crossing based on young subjects may serve as a baseline for further studies on the older group for a better understanding of the mechanisms and the prevention of falls in the elderly.

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