Age effects on strategies used to avoid obstacles

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Summary

Chen et al.[1] found that the rates of success which 24 healthy younger and 24 healthy older adults achieved in not stepping on fixed and suddenly appearing virtual obstacles was adversely affected by reducing their available response time. This paper reports the gait strategies used by those 48 subjects in avoiding the obstacles and the factors associated with falls by four of the subjects. Differences among gait parameters were analysed with respect to age, gender, available response time, and avoidance strategy. Both short- and long-step strategies were used to avoid stepping on the obstacles, but age differences in strategy choice were not significant. The short-step strategy was used more often with shorter available response times. To avoid a fixed obstacle gait was seldom adjusted more than two steps before reaching it; the older adults, however, adjusted their stepping pattern one step earlier than did the younger adults. As the available response time was shortened, the results suggest that older adults had more difficulty than did younger adults in employing the long-step strategy. Although the short-step strategy is easier to employ at short available response times, it becomes a highly risky strategy when combined with a fast walking speed and resulted in actual falls. The results show that in both young and old healthy adults, tripping does not necessarily originate from contacts with a physical obstacle; it can be self initiated.

Key words: Gait, trips, falls, ageing, obstacle avoidance strategies

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Introduction

Although tripping over obstacles is one of the most common causes of falls in the elderly[2–5], few studies have focused on how either young or old adults negotiate obstacles. Patla et al.[6] examined the dynamics of gait adjustments that young adults made when using visual cues to step over obstacles and alter direction. They showed that when cued one step ahead, young adults are able to avoid low obstacles. Subjects systematically manipulated their gait patterns as a function of obstacle height, position and the time available within the ongoing step. Their results also suggested that with shorter cue times, changing direction is more difficult than stepping over obstacles directly. McFadyen and Winter[7] performed kinematic and kinetic analyses of the lower limb anticipatory locomotor adjustments employed by subjects of unspecified ages while stepping over obstacles. Their results showed that when confronted with obstacles, subjects decreased their hip pull-off activity and employed a strategy favouring knee flexion. In the first study of the effects of ageing, Chen et al.[8] reported the gait patterns of healthy younger (YA) and older (OA) adults as they approached and stepped over fixed obstacles of different heights. The OA did not have more difficulty than YA in approaching and stepping over obstacles of different heights, but their avoidance strategies were more conservative in that they used slower crossing speeds and placed the obstacles further forward in their crossing step. Moreover, the OA inadvertently contacted the obstacle significantly more frequently than did the YA. Chen et al.[1] recently reported the rates of success of another 24 healthy YA and 24 OA subjects in

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stepping over virtual obstacles that were fixed or that appeared so as to provide available response times ranging from 200 to approximately 1000 ms. Age differences in rates of success were found to be small.

Whether OA adopt different strategies from those of YA in negotiating obstacles with short cue times is unknown. It seems worthwhile to make such inquiries, specifically to explore possible causes of tripping among the elderly and generally to learn how mobility task performance is altered by natural ageing. The present paper analyses the gait patterns used by the subjects in the Chen et al.[1] study to avoid stepping on the virtual obstacles. Its principal objective was to test the null hypotheses that neither age, gender, nor available response times affect the strategies used to step over an obstacle appearing with short available response times. Moreover, during these walking trials, four subjects fell while trying to avoid the virtual obstacle. The paper will also describe the circumstances of those falls.

Methods

Many of the methods used in this study are described in detail by Chen et al.[1] Only a brief outline of those will be given here. Two groups of subjects were tested: 24 healthy young adults (YA: 12 female, 12 male) with a mean age of 23.4 years and 24 healthy old adults (OA: 12 female, 12 male) with a mean age of 72.8 years.

An 8-m walkway was used with a conducting surface 5.76 m long and 1.20 m wide. The surface was instrumented with 8-m wide transverse conductive aluminium tape strips separated by 2-mm intervals. These were linked to a computer to yield foot position data to 1 cm accuracy. The computer used the timing and locations of the first few foot strikes to update predictions of the next two footfall locations along the walkway. It then used this information to decide at which impending footfall location it would place a virtual obstacle, according to a standardized, prearranged, randomized trial sequence. The virtual obstacle consisted of a band of light projected onto the walkway surface across the subject's path by a servo-controlled mirror. The virtual obstacle was synchronized to the subject's stride pattern and made to appear at the predicted position of the subject's next footfall so as to give available response times (ART) of 200, 250, 300, 350, 400, or 450 ms, and two step lengths before heel strike, corresponding to an ART of approximately 1000 ms. Fixed virtual obstacles placed 4 m from the beginning of the walkway prior to the start of the walk were also used. A total of six trials for each of these eight conditions were presented and grouped into three blocks.

During the testing, subjects wore a pair of flat-soled shoes each with 2-cm wide conducting strips attached under the heel and metatarsal heads. A flexible cable connected the strips under the shoes to the computer via a belt. For safety, each subject wore a lightweight body harness attached to 3.3-m high overhead track via a cable whose length was adjusted so that the harness prevented the hands and knees of the freely suspended subject from touching the ground. A staff member walked slightly behind and to the side of the subject to assist in the event of a fall. Subjects started from standing on a start-trigger pad 1 m ahead of the conducting surface region. They were instructed to walk along the walkway 'at a comfortable speed', to 'try to avoid stepping on the obstacle' should it appear unpredictably anywhere along a 3-m stretch of the walkway, and continue to the end of the walkway. Gait speed was monitored and kept to at least 90% of subject obstacle-free gait control values. Step length was defined as the distance between the metatarsal strips of consecutive stance feet; step time was defined as the interval between consecutive metatarsal strip-floor contact times.

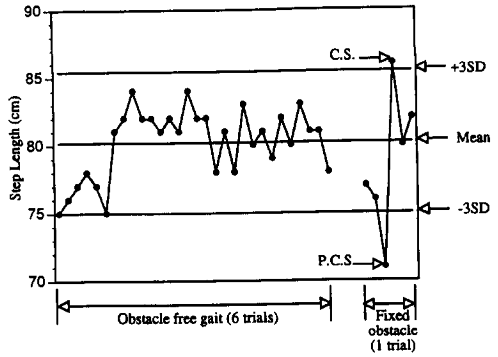
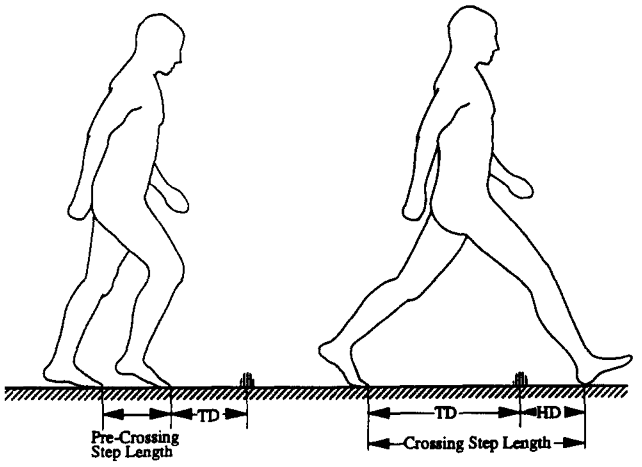


Figure 1. Sample step length control chart derived from six obstacle-free gait trials. Mean ± 3 SD values are shown. Data for a fixed-obstacle trial are also shown. C.S., crossing step; P.C.S., precrossing step

Subjects' gait was observed in three tasks: (1) walking normally; (2) stepping over fixed virtual obstacles; and (3) stepping over virtual obstacles which appeared suddenly, without warning and at varying locations. Final precrossing step length and time, crossing step length and time, pre-obstacle toe distance (TD) and post-obstacle heel distance (HD) were calculated for each trial. In addition the number of steps over which deliberate adjustments (described subsequently) were made to avoid obstacle contact was noted, as was, in the sudden-appearance trials, the crossing strategy (described subsequently) used. To analyse when deliberate step adjustments involved in stepping over the fixed obstacle were first made, control charts[9] of step lengths and step times were constructed for each subject. These, using data collected in six normal, obstacle-free walking trials of approximately seven steps each, represented a ±3 SD normally distributed range of step lengths and times. These charts were used to check the step lengths and times in the fixed obstacle trials. Step lengths and times lying outside of the 3-SD bounds were considered to have resulted from deliberate adjustment of the stepping pattern (Figure 1). The scheme was then validated in the two-steps-ahead obstacle trials (see Results).

Before the obstacles' appearance in the sudden-appearance trials, subjects walked normally and no significant adjustments in step length and time were needed. After the obstacle's appearance, and because of the obstacle's location and short ART allowed, subjects had



(A) Short Step Strategy (B) Long Step Strategy

Figure 2. a Short-step (SSS), and **b** long-step (LSS) strategies.

only two choices in order to avoid stepping on it: they could either choose to shorten their normal step and then take an extra crossing step, or they could choose to take a longer crossing step. These strategies will be referred to as a short step strategy (SSS) and a long step strategy (LSS) (Figure 2). Because trials in which subjects contacted the obstacle meant that neither the SSS nor the LSS was employed, they were not further analysed as to strategy employed. We did not attempt to identify strategies used during the fixed-obstacle trials, since the obstacles were in view of the subjects even before they started walking.

Age, gender, and ART effects on all parameters were tested by repeated measures ANOVA with $P < 0.05$ considered significant. Both absolute values of the parameters and values normalized to subject body heights were examined. The ANOVA was performed only for trials with ART greater than 250 ms, corresponding to rates of success of 50% or more. Too few successful trials occurred when ART was less than 300 ms to achieve adequate statistical power. Means and SDs of each parameter are reported, mostly according to age, ART, and strategy group. The significance of differences in the proportions of subjects groups using particular strategies or who fell were examined using the binomial test.

All trials were videotaped from a superior–posterolateral view. When a fall occurred, the circumstances of the fall were identified by reviewing the video tape and reporting qualitative observations of the event together with the subjects' mean walking speed and the measurements of stepping strategy used during that trial.

Results

General

In obstacle-free gait, compared to females, males took significantly longer steps (75.9 cm *versus* 70.4 cm) and longer step times (548 *versus* 511 ms). Mean walking speeds did not differ significantly, but females had faster normalized walking speeds (Table 1).

Effect of decreasing ART on choice of obstacle crossing strategy

The fixed-obstacle tasks allowed the longest ART. In those tasks the earliest the YA significantly adjusted their step length approaching the obstacle was less than three steps ahead (Figure 3). At an average gait speed of 1.38 $m\ s^{-1}$ this represents an effective ART of approximately 3 s. The OA modulated their step length one step earlier than the YA. Similar results were found for step time, since it was highly correlated with step length. The earliest the YA adjusted their step time was three steps prior to crossing, whereas the OA modulated theirs four steps prior to crossing the obstacle (Figure 4). However, the YA most often waited to adjust their step length and step time at the crossing step, whereas the OA most often adjusted their step length one step ahead of the crossing step.

For the two-steps ahead task with its ART of 1000 ms or more, the YA and OA used SSS in 30.1 and 39.6% of the trials respectively (Table 2). In a total of 144 two-steps ahead trials for each age group, all the YA stepped over the obstacle successfully but the OA failed to do this in seven trials (binomial test, $P < 0.001$). Six of those failure trials showed evidence of an inadequate LSS in these OA: the step was simply not lengthened enough for the heel to clear the obstacle.

When the ART was decreased from 450 to 300 ms an analysis of the strategies used by the YA and OA to successfully avoid virtual obstacles shows that OA systematically decreased their use of the LSS in proportion to the decrease in the ART (Table 2). The YA adjusted their choice of strategy to an even more marked extent. Both YA and OA employed a strategy for the 450-ms ART similar to that used for the two-steps ahead task, but the OA used the LSS approximately 8–9% less often (Table 2). When stepping over an obstacle, whether using an SSS or an LSS, males took significantly longer crossing step lengths than females. Below 300 ms ART subjects could not obtain success rates above 50%, rendering those results sufficiently unreliable to warrant not reporting them.

By definition, both YA and OA shortened the step that would have resulted in obstacle contact when the SSS was used for obstacle avoidance. For example, in the 450-ms ART task it was shortened by approximately 37% (27.1 and 25.8 mm) from fixed-obstacle control values (Table 3). Toe distances decreased systematically and significantly over tasks when ARTs were decreased from 450 to 300 ms. However, the mean toe distances measured in the 400- and 450-ms tasks were longer than those measured in the two-step-ahead task with its 1000-ms ART. Since the incremental changes in mean crossing toe distance between 450 and 300 ms were so consistent, this suggests that the lengthened toe distance exhibited in the 1000-ms ART task is evidence of a different step

Table 1. Mean ± SD Normal walking speed

Walking speed/group	YF	YM	OF	OM
Absolute (m/s)	1.36 ± 0.08	1.39 ± 0.20	1.41 ± 0.18	1.39 ± 0.11
Normalized (body length/s)*	0.832 ± 0.042	0.795 ± 0.117	0.895 ± 0.099	0.799 ± 0.053

*P = 0.015, gender ANOVA.

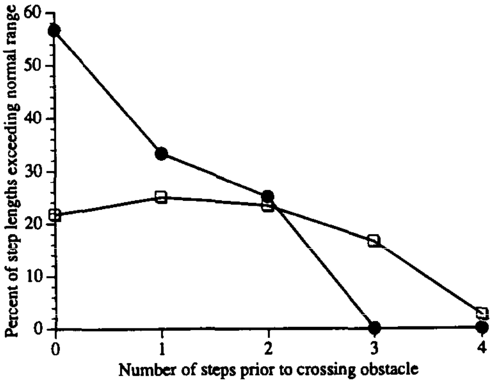


Figure 3. Percent of step lengths (SL) falling outside the normal range for steps occurring prior to crossing a fixed virtual obstacle. ● young SL; □ old SL.

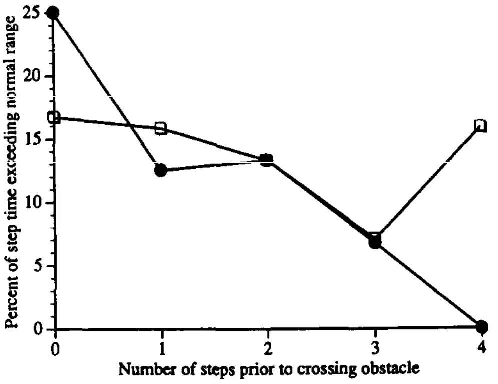


Figure 4. Percent of step times (ST) falling outside the normal range for steps occurring prior to crossing a fixed virtual obstacle. ● young ST; □ old ST.

length control strategy in the two-step-ahead task (see Discussion). Because no significant age differences in any of the step parameters listed in Table 3 were found we conclude that the OA used the same crossing pattern as the YA did when using the SSS to avoid stepping on the virtual obstacle.

When the LSS was used to step over the obstacles (Table 4) the crossing step length was approximately 30% longer than that used for SSS or fixed-obstacle trials. For example, YA and OA lengthened their mean step by 27.6 and 25.8 cm in the 450-ms ART trials. YA used a significantly longer step length and step time than OA (Table 4). This would appear to correlate with the decreased use, noted above, by OA of the LSS in tasks with 450-ms ART or more.

Falls

Three OA (1 male, 2 female) and one YA (male) completely lost their balance and fell during a sudden-appearance trial, despite there being no physical obstacle. All four fallers had walking speeds normalized to stature that were faster than the mean for their individual gender groups. The subjects were not able to regain their balance by taking extra steps. Their falls were ultimately arrested by the safety harness without any injuries. Videotape recordings were available for three and stepping kinematics data for all four of the falls. For the one fall that was not taped (due to a technical problem), which involved the YA male, fall circumstances were reconstructed from the kinematics data and other taped trials showing the avoidance strategies he consistently used.

All falls occurred at short ARTs: two of the falls occcurred in a 250-ms, one in a 300-ms, and one in a 450-ms ART trial (Table 5). Those subjects who fell in the trials with less than 450-ms ART had achieved a rate of success of 1.0 for trials with ARTs 100 ms or longer than the ART for the trial in which they fell. So those that fell did not have inferior performances at longer ART. None of the falls involved use of an LSS. Two of the falls (one YA, one OA) began prior to the crossing step after an SSS was undertaken to avoid stepping on the obstacle. The precrossing step length and step time used in the trial in which those subjects fell were not significantly different from those they used in other successful trials with an SSS and the same ART. The other two falls (two OA) occurred when the subjects began to step on the obstacle and, in a belated avoidance manoeuvre, tried to avoid lowering the forefoot in one case and the rearfoot in the other onto it. This caused them to begin to fall in an anterolateral direction. One of the subjects then had his swing foot toe contact the floor prematurely and an anterolateral trip then occurred. The other OA could not take extra steps rapidly enough to regain her balance.

Methodological validation

The reliability of the control chart scheme was validated in the two-steps-ahead ART sudden-appearance trials. No significant adjustments were found in either the SSS or LSS groups before the obstacle appeared (see SSS data for number of steps before crossing > 2, and LSS data > 1, Table 6). This is as it should be since one does not adjust step length before an obstacle appears. A noteworthy difference was that in the SSS both step length and step time were modulated most frequently one step ahead of the crossing step, while in the LSS they

Table 2. Percent of subjects choosing each strategy, by age and ART

Task		300-ms ART	350-ms ART	400-ms ART	450-ms ART	Two-step-ahead (approx. 1000-ms ART)
SSS	YA	52.6	59.5	43.4	27.5	29.1
	OA	56.8	54.9	39.8	35.9	39.6
LSS	YA	47.4	40.5	56.6	72.5	70.9
	OA	43.2	45.1	60.2	64.1	60.4

Table 3. Kinematics of the short-step strategy. For each parameter the upper line gives the YA mean ± SD values, while the lower line gives corresponding OA values

	Available response time						
Parameter	300 ms	350 ms	400 ms	450 ms	2-Step 1000 ms	Fixed Obstacle	Obstacle Free
Precrossing	54.4 ± 6	53.3 ± 7	50.2 ± 8	46.2 ± 9	53.2 ± 6	73.3 ± 6[*]	74.2 ± 6[‡]
step length (cm)	54.3 ± 6	49.8 ± 8	47.1 ± 10	42.3 ± 15	52.7 ± 10	68.1 ± 11	71.9 ± 7
Precrossing	467 ± 73	470 ± 53	434 ± 48	439 ± 70	419 ± 43	544 ± 54[‡]	542 ± 39[‡]
step duration (ms)	440 ± 44	427 ± 66	425 ± 108	397 ± 68	437 ± 46	522 ± 58	517 ± 46
Crossing step	77.8 ± 6	75.7 ± 8	79.5 ± 7	78.4 ± 8[†]	77.6 ± 6	80.2 ± 7[*]	N/A
length (cm)	75.4 ± 9	77.1 ± 10	79.4 ± 10	80.2 ± 10	78.4 ± 6	75.9 ± 10	
Crossing step	532 ± 98	505 ± 83	543 ± 51	522 ± 73	512 ± 48	581 ± 52	N/A
duration (ms)	513 ± 79	517 ± 100	511 ± 76	515 ± 75	547 ± 45	567 ± 71	
Crossing toe	7.3 ± 4	9.6 ± 4	12.2 ± 7	14.0 ± 7[§]	10.5 ± 4	24.7 ± 8	N/A
distance (cm)	7.2 ± 4	11.7 ± 8	15.9 ± 9	20.4 ± 8	14.7 ± 6	22.5 ± 8	
Crossing	42.4 ± 5	37.8 ± 5	39.2 ± 5	36 ± 13	39.2 ± 6	27.2 ± 9	N/A
heel distance (cm)	40.4 ± 8	38.1 ± 9	35.6 ± 7	31.6 ± 10	35.8 ± 7	25.8 ± 7	

[*] $P<0.001$, gender ANOVA.
[†] $P<0.018$, gender ANOVA, conducted for ART 300 – 450 ms task.
[‡] $P<0.006$, gender ANOVA.
[§] $P<0.001$, ART (available response time) ANOVA, conducted for ART 300–450 ms task.

Table 4. Kinematics of the long-step strategy. For each parameter the upper line gives the YA mean ± SD values, while the lower line gives corresponding OA values

	Available response time						
Parameter	300 ms	350 ms	400 ms	450 ms	2-Step 1000 ms	Fixed Obstacle	Obstacle Free
Precrossing	76.1 ± 7	76 ± 6	75.9 ± 6	76.4 ± 7[**]	80.9 ± 8	73.3 ± 6[*]	74.2 ± 6[‡]
step length (cm)	74.3 ± 9	72 ± 9	72.8 ± 8	72.9 ± 9	77.6 ± 10	68.1 ± 11	71.9 ± 7
Precrossing	546 ± 44	539 ± 38	550 ± 41	551 ± 34[**]	593 ± 50	544 ± 54[‡]	542 ± 39[‡]
step time (ms)	516 ± 50	500 ± 55	517 ± 51	522 ± 58	555 ± 58	522 ± 58	517 ± 46
Crossing step	106.4 ± 9	105.8 ± 9	103 ± 8	104 ± 8[*§°]	95.9 ± 6	80.2 ± 7[*]	N/A
length (cm)	103 ± 15	96.3 ± 11	100 ± 14	98.7 ± 12	94.4 ± 11	75.9 ± 10	
Crossing step	675 ± 55	684 ± 54	661 ± 62	669 ± 64[†¶]	602 ± 49	581 ± 52	N/A
time (ms)	640 ± 82	572 ± 147	626 ± 68	639 ± 70	588 ± 66	567 ± 71	
Crossing toe	61 ± 5	61.5 ± 7	58.4 ± 7	59.7 ± 6[‡]	53.4 ± 7	24.7 ± 8	N/A
distance (cm)	58.9 ± 10	54.3 ± 10	59.2 ± 8	57.4 ± 7	51.5 ± 9	22.5 ± 8	
Crossing	17.2 ± 6	15.9 ± 8	16.3 ± 8	18.6 ± 6	14.3 ± 5	27.2 ± 9	N/A
heel distance (cm)	17 ± 12	14.8 ± 7	13.4 ± 8	13.8 ± 7	18.7 ± 16	25.8 ± 7	

[*] $P<0.001$, gender ANOVA.
[‡] $P<0.006$, gender ANOVA.
[**] $P<0.013$, gender ANOVA.
[†] $P<0.014$, age ANOVA, conducted for ART 300–450-ms tasks.
[§] $P<0.041$, age ANOVA, conducted for ART 300–450-ms tasks.
[°] $P<0.018$, gender*age ANOVA, conducted for ART 300–450-ms tasks.
[¶] $P<0.006$, ART*age ANOVA, conducted for ART 300–450-ms tasks.

were modulated most frequently at the crossing step (Table 6)

Discussion

This is one of few studies to analyse the strategies used by humans to adjust their gait in order to step over an obstacle with short available response times. Once the virtual obstacle appeared, subjects were forced to adopt one of two strategies if they were to avoid it: either they had to shorten their precrossing step or they had to lengthen their crossing step. Different outcomes were associated with the two different crossing strategies. The salient findings are that when short available response times limit their options, humans approaching an obstacle: (a) often adopt a short step strategy in order to

Table 5. Information on the subjects who fell

Subject	ART at fall	Speed (m/s)	Normalized speed (stature/s)	Rate of success				
				250 ms	300 ms	350 ms	400 ms	450 ms
YM‡	250 ms	1.717	0.933	0.50	0.92	1.00	1.00	1.00
OM†	450 ms	1.401	0.801	0.25	0.33	0.58	0.67	0.75
OF*	300 ms	1.366	0.962	0.08	0.33	0.67	1.00	0.92
OF‡	250 ms	1.586	1.004	0.67	0.50	1.00	1.00	1.00

‡Overshortened step to avoid obstacle at fast speed.
†Fixed stance foot ankle, swing foot toe caught the ground and lost balance laterally.
*Fixed stance foot ankle and lost balance.

Table 6. Percent of trials in the two-step-ahead task with precrossing step lengths and times outside the normal range (±3 SD)

		No of steps before crossing					
		0	1	2	3	4	5
Short-step strategy (SSS)	Step length	26.3	88.9	20.2	2.0	0.0	0.0
	Step duration	13.1	76.8	9.0	0.0	2.0	0.0
Long-step strategy (LSS)	Step length	96.7	46.5	0.0	0.0	0.0	0.0
	Step Time	80.8	44.4	1.0	0.0	0.0	0.0

step over it, but (b) in so doing, place themselves at risk for a self-initiated fall caused not by physical contact with the obstacle but by the change in crossing strategy provoked by the time-critical nature of the task. In contrast, when 400 ms or more response time was available, approximately two-thirds of all subjects selected the less risky (see below) LSS. This switch in obstacle avoidance strategy from SSS to LSS when time permits may reflect the recognition that, even though the task is now easier, the LSS is safer through it may not necessarily be physically less demanding. While the results provide direct evidence for the greater safety of the LSS, the evidence that subjects, particularly OA, found the LSS more difficult to execute is more indirect and comes principally from examining age group differences.

When they adopted the SSS the OA used the same crossing step pattern as the YA, but OA used the SSS 8–10% more often than the YA did in crossing obstacles with 450 ms or longer ART. Increased use of the SSS may represent a more conservative behaviour by OA. When using the SSS OA used a longer TD and shorter HD than the YA. Similar conservatism was reported in OA approaching and stepping over fixed physical obstacles of different heights[8]. In that study subjects limited how close to the obstacle they allowed their stance foot toe to come. When using the SSS, for example, the effects of abbreviating their pre-obstacle step allowed them to increase toe distance by at least 6 cm if the ART was increased from 300 to 450 ms, whereas heel distance did not change (Table 3). However, this strategy proved dangerous if carried to an extreme; if the precrossing step were shortened excessively a fall could result (see below). The result that OA used a different behaviour in the two-steps-ahead task for controlling TD than in the 300–450 ms (see Results) suggests that subjects made a speed–accuracy trade-off. In the latter task, with little time available, subjects appear to have resorted to an abrupt, perhaps reflexive, knee flexion in order to jerk the foot back in an attempt to prevent it from landing on the obstacle. The more time they had the farther back it travelled. On the other hand, in the two-steps-ahead task, they had more than twice as much time to plan an accurate crossing step. In other words with short ARTs step accuracy may be sacrificed in favour of a less accurate, but more successful, and more risky, strategy for avoiding the obstacle.

Why was the LSS more difficult for OA to execute than the SSS under short ART? We argue that the reason is unlikely to be due to an age difference in central processing time because of the fact that the age difference in rates of success in crossing the obstacle were barely statistically significant[1]. Rather we suspect the reasons may be biomechanical. Firstly, the SSS requires a knee flexion moment to overcome shank inertia and jerk the foot backwards relative to the obstacle on which it would otherwise land. In contrast because the knee already is extended the LSS requires a hip flexion moment to accelerate the foot forward of the obstacle. Because of the difference in leg and shank inertias, the required LSS hip flexion moment must be larger than the SSS knee flexion moment. The SSS is also easier for the OA to accomplish because knee flexor strength generally exceeds that of the hip flexors[10]. In addition, because the rate of developing joint moment is nearly halved in OA relative to YA[11], OA require a longer time to develop the greater LSS hip flexion torque. So biomechanical constraints may rule out too sudden an increase in crossing-step length when ARTs are short, particularly for OA.

Indirect evidence that the LSS may be physically more demanding than the SSS comes from the fact that OA displayed greater difficulty than YA in suddenly lengthening their normal step length by nearly 40% in order to cross the obstacle when the ART ranged between 300 and 450 ms. For example, OA had significantly shorter crossing step lengths and times using the LSS than the YA. Moreover, even when longer ARTs were available, six of seven failures in crossing the virtual obstacle given a two-step-ahead warning occurred when OA subjects tried to use an LSS to step over the virtual obstacle but contacted it with their heels, again illustrating the difficulty of suddenly executing the LSS.

Methodological aspects

The virtual obstacle used in this study consisted of a narrow rectangular lighted area on the ground across the walkway, akin to a space between concrete sidewalk slabs. However, in contrast to a physical obstacle it could not physically interfere with the subject in any way. When programmed to appear suddenly and inconveniently at an impending footfall location, it successfully mimicked a hazard that comes to one's attention at the last instant. Because no practice effects in avoiding this suddenly appearing obstacle were found[1] we assume the avoidance task was both familar and realistic.

The obstacle-free gait speeds, step lengths and step times found in this study for the two age groups agreed well with those reported by Cunningham et al.[12], Hageman and Blanke[13], Blanke and Hageman[14], Kadaba et al.[15], and Winter et al.[16], although the speed used by the OA was slightly faster than that reported by Murray et al.[17]. Thus subjects' gait in this study did not differ significantly from that exhibited in other studies, despite use of a safety harness, a trailing umbilical cable, and the complex measurement equipment. No significant practice or fatigue effects were found in this study[1].

The strategies subjects used in stepping over the fixed obstacle were also analysed using the control chart technique, but results were not divided into LSS or SSS because the obstacle was not necessarily located where subjects might step on it. Moreover, in the fixed-obstacle trials subjects usually employed combinations of lengthening and shortening steps before crossing the fixed obstacle. The fixed obstacle trials served, however, as a control for the suddenly appearing obstacle trials in that the subjecct essentially has unlimited ART – more than 3s – to make their gait adjustments. In the fixed-obstacle task subjects had the luxury of being able to plan their stride pattern to avoid stepping on the obstacle over a distance of more than 4 m. Yet we found the YA waited until the final step to modulate their crossing step length and time more often than the OA did. Conversely the OA displayed a more conservative approach by adjusting their stride pattern one or two steps earlier than the YA. Though all the OA successfully crossed the fixed virtual obstacle, we found seven failures among the 144 trials involving crossing the virtual obstacle with a two-step-ahead warning. Six of those failures, in which the subject inadvertently stepped on the obstacle, occurred when OA subjects tried to use a LSS to step over the virtual obstacle and contacted it with their heels. This is consistent with our earlier finding that OA have a higher risk of obstacle contact, especially at the heel, while stepping over a physical obstacle[8].

The use of control charts is a novel statistical quality control technique to analyse human gait patterns. Was the control chart scheme sufficiently sensitive and reliable to identify meaningful differences in step adjustment patterns? We think so because when the control charts were used to classify the two-step-ahead data, deliberate adjustments were found in only 2% of the steps taken before appearance of the virtual obstacle. This confirms that the subjects did not anticipate when or where the obstacle would appear during these experiments, even with practice. It also confirms that the error associated with using the control chart scheme in the fixed obstacle trials was less than 2%. The scheme was not required for analysis of obstacle trials with short ART or obstacle positions programmed to appear at subject's next footfalls because the strategy the subject used to actually step over obstacles can be directly identified from their next footfall locations.

This study is concerned with examining the effect of age on the stepping strategies used to avoid an obstacle. This differs from the only other study to examine time-critical obstacle avoidance, namely that of Patla et al.[6], in that rather than examine step lengthening or shortening strategies in avoiding a virtual obstacle appearing at an unknown location, they examined the ground reaction forces and muscle coordination employed by YA to step over two different height physical obstacles which appeared at a known and fixed location. Although both studies varied the ART Patla used only two ARTs, of one and two step duration, approximately equivalent to 500 and 1000 ms.

What factors limit obstacle avoidance at short notice? On detecting the object visually, cognition is needed to recognize it as an obstacle. The likelihood of foot–obstacle contact then needs to be estimated, given the current stride pattern and gait speed. If contact is deemed likely, a LSS or a SSS response must not only be selected, but must also be executed in a short time interval. How long does this process take? Simple reaction time (SRT) experiments using a visual cue showed the shortest average latency for an observable increase in ankle moment was approximately 200 ms (Ashton-Miller et al., unpublished); however, no choice of strategies had to be made and negligible foot movement was required. In the present experiment obstacle avoidance rates of success of 25 and 95%, for example, required 225 and 450 ms ART, respectively[1]. In comparison to the lower extremity SRT latency, the additional 30 ms (225–195 ms) permitted a 25% success in obstacle avoidance; on the other hand, an additional 255 ms (450–195 ms) allowed a nearly fourfold improvement in success rate, to 95%. Because rates of success were similar in YA and OA[1], their central processing times would not seem to differ much in this task. Both the fact that the LSS was reserved for the longer ART values, and the fact that the OA had relatively greater difficulty implementing the LSS at shorter ART, suggest a biomechanical, rather than a central processing time constraint may limit OA use of the LSS at short ART. Simulations show[18] that the most likely biomechanical constraint appears to be the approximately 30% reduction in the rate of developing lower extremity strength in OA[11]. At short ART the YA, and especially the OA, apparently recognized that there was not enough time to develop the requisite lower extremity joint moments needed to reliably execute the LSS.

Falls

Four falls occurred in the course of this study, but none involved contact with a physical obstacle. That falls can be self-initiated in the face of a perceived, but not real, threat is a new although not unexpected finding. Moreover, this is the first time that falls have been caused in the laboratory without physically obstructing a subject. All four falls involved faster-than-normal walking speeds. All of the sudden-appearance obstacle trials involved avoidance manoeuvres that had to be completed within 200–450 ms. In a caveat to those who might risk performing such studies without a safety harness, the four falls occurred so fast that laboratory personnel alongside the subject could not react fast enough to stop any of them.

What were the circumstances of the falls? Two were associated with a sudden shortening of the precrossing step. During normal gait the forefoot of the swing foot is placed to strike the ground well anterior of the body's centre of mass (CM). This temporary extension of the support base is a biomechanical requirement to prevent an anterior fall during this phase of gait. The two subjects who used the SSS and fell did so because they shortened their precrossing step to the point where their CM was so far forward of their support base that they could not recover balance even by taking additional steps.

Two other falls occurred in the OA when, after foot strike, they tried to avoid lowering the forefoot or heel onto the obstacle. This caused them to lose their balance and fall anterolaterally to the swing-foot side. This late avoidance manoeuvre was used by the YA in 18.5% of their 864 sudden-appearance trials, and none fell when using it[1]. The OA used the manoeuvre in only 10.9% of their trials, but that is where these two falls occurred. The fact that the two falls were anterolateral is of interest because lateral falls have been associated with a high rate of hip fractures in the elderly[19].

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