Abilities To Turn Suddenly While Walking: Effects of Age, Gender, and Available Response Time

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Background. Falls may occur when an unexpected turn must be made quickly, in order to avoid colliding with an object in the gait path. Little is known about abilities, particularly about abilities of old adults, to turn suddenly.

Methods. Twenty young and 20 old (mean age 73.8) healthy and physically active adults, while walking straight ahead, were cued to make approximately a 90° turn without advance knowledge of where the turn was to be made or whether it would be to the right or left. Subjects were given available response times (ART), the times between the cue to turn, and potential crossing of a specified forward limit line, of 375, 450, 600, and 750 ms. The rate of success (RS) in completing the turns as prescribed was determined. Regression analyses were used to estimate the additional ART that would be needed for other groups to achieve the same RS as did the young male subject group.

Results. For all ART, old subjects had a lower rate of success in completing the turns as prescribed than the young. At an ART of 375 ms, mean RS was 36% for the young and 6% for the old. The regression analyses suggested that, for RS from 30 to 95%, old adults needed 112 ms longer than young of corresponding gender to succeed as well. Females needed an ART of 50 ms longer ART than males of corresponding age.

Conclusions. There are significant age and gender differences among healthy and physically active adults in the available response times they need when walking for successfully making sudden turns.

APPROXIMATELY 90% of hip fractures occur in connection with a fall (e.g., 1–3). Cumming and Klineberg found in their epidemiological study (3) that a hip fracture was 7.9 times more likely to occur when falling while turning than when falling while walking straight. Falling while turning may occur when an unexpected turn must be made quickly, such as when a gait path obstacle that is too large to be maneuvered around comes suddenly to attention.

Little is known about abilities of either young or old adults to turn suddenly at an unknown location and to an unknown side. We undertook the current study to examine performance abilities of healthy adults asked suddenly to turn under these conditions. The effects of available response time, age, gender, and side-of-turn upon rates of success in making those turns were quantified. Chen et al. (4), in their study of abilities to step over obstacles that suddenly appeared in the gait path, found age and gender effects on rates of success to be nonsignificant, but available response time effects to be significant and substantial. Based on the Chen et al. study, and given the similarities between it and the present study focusing on musculoskeletal and neurological items, our null hypotheses were that the present study would produce findings similar to those of Chen and colleagues.

METHODS

Subjects. — Forty healthy volunteer subjects were studied. They were divided into four groups of 10 subjects each: young adult females (YF) and males (YM) and old adult females (OF) and males (OM). The young adults (YA) were recruited among university students; the old adults (OA) were independently dwelling community residents. Informed consent of each subject was obtained prior to testing. Mean ages of the YA and OA groups were 21.8 and 73.8 years (Table 1). All subjects comfortably walked at speeds within 10% of 1.3 meters/second (m/s).

All YA and OA denied histories of significant diseases, visual impairment not correctable with glasses, otologic or neurological disease, recent limb or spinal fracture, other musculoskeletal impairments, or persistent symptoms of vertigo, lightheadedness, or unsteadiness. OA also underwent a more detailed medical history and physical examination focusing on musculoskeletal and neurological items, similar to that described by Alexander et al. (5). With few exceptions, YA and OA reported that they regularly engaged in exercise, physical activity, or sports programs.

Subjects wore flat-soled athletic shoes and a lightweight, waist-level safety harness. The safety harness tether and a subject instrumentation cable were held by a staff member who walked behind the subject.

Equipment, measurements, and protocol for trials. — Signals to turn suddenly were presented to the subjects as they walked along an 8 m by 1 m walkway (Figure 1). This walkway incorporated five poles per side that were hung from the ceiling at 1 m intervals along the walking path and were wrapped with Christmas-tree lights. Each pair of adjacent poles formed a gate, so there were four gates per side.
Table 1. Overview of Subject Characteristics (Mean ± SD)

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Age (yr)</th>
<th>Body Mass (kg)</th>
<th>Height (m)</th>
<th>Comfortable Walking Speed (m/s)</th>
<th>Comfortable Turning Speed (m/s)</th>
<th>Normal Stride Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young Female (YF)</td>
<td>10</td>
<td>20.4 ± 2.0</td>
<td>68.2 ± 7.3</td>
<td>1.72 ± 0.06</td>
<td>1.33 ± 0.06</td>
<td>1.06 ± 0.03</td>
<td>1.38 ± 0.07</td>
</tr>
<tr>
<td>Young Male (YM)</td>
<td>10</td>
<td>23.1 ± 3.7</td>
<td>75.7 ± 10.6</td>
<td>1.76 ± 0.07</td>
<td>1.32 ± 0.06</td>
<td>1.01 ± 0.07</td>
<td>1.44 ± 0.07</td>
</tr>
<tr>
<td>Old Female (OF)</td>
<td>10</td>
<td>76.5 ± 4.4</td>
<td>62.6 ± 7.2</td>
<td>1.57 ± 0.09</td>
<td>1.31 ± 0.08</td>
<td>1.01 ± 0.07</td>
<td>1.31 ± 0.05</td>
</tr>
<tr>
<td>Old Male (OM)</td>
<td>10</td>
<td>71.0 ± 3.2</td>
<td>73.5 ± 7.6</td>
<td>1.76 ± 0.06</td>
<td>1.34 ± 0.05</td>
<td>1.03 ± 0.05</td>
<td>1.49 ± 0.10</td>
</tr>
</tbody>
</table>

Subjects were told to turn into a particular gate if the lights on the forward gate pole were illuminated. Beyond each gate, there was a clearly marked 1 m long by 0.8 m wide exit path perpendicular to the walkway. Subjects were told to keep their steps within the designated exit path and continue to walk without substantial slowing until they passed the marked end of the exit path. Subjects were told that if no gate pole lights were lit, they were to keep walking straight ahead at a comfortable pace.

Pole lighting was controlled by computer. A 90 ms total delay in switching on the lights was found to be constant, so the computer command to turn pole lights on was issued 90 ms ahead of the desired lights-on time. The relay used to switch on the lights provided a noticeable audible signal to the subject that lights on one of the poles were being switched on. The sound and light stimuli occurred essentially simultaneously.

Subjects' motions were measured by an Optotrak (Northern Digital Corp., Waterloo, Ontario) optoelectronic camera system placed at the end of the walkway. This measured in three dimensions the approximate locations of the two ankles, two knees, and the whole-body center of mass (CM), using six pairs of infrared-emitting diodes attached to the subject (Figure 2). Diode pairs were affixed to the subject with straps just above the tongue of each shoe and just above each kneecap. Two diode pairs on a short rigid wand were placed over the umbilicus to locate approximately the CM.

At the start of a trial, subjects were instructed to stand at a designated one of eight starting lines marked on the walkway. The forward-most starting position was 0.8 m ahead of the first set of poles, so that subjects could, as shown by Chen et al. (4), achieve their comfortable walking speeds before entering the Gate 1 area.

Two sets of preliminary trials were conducted: straight-walk-control and comfortable-turn-control trials. After two warm-up trials, six straight-walk-control trials were used to determine average comfortable walking speed and initial and normal stride lengths. For these, subjects were told that no lights would appear and were asked to walk at their comfortable pace. Speeds and stride lengths were averaged over those six trials. Comfortable walking speed was calculated from the time needed for the CM diode to travel 0.8 m upon entering the Gate 1 area. Normal stride length was that of the stride immediately after the initial stride.

Four comfortable-turn-control trials followed, to measure average comfortable turning speed and so provide a basis to determine whether subjects slowed more than allowed when turning. In these, subjects were told before the trial began to turn at Gate 2 in a given direction. Two of the prescribed
comfortable turns were to the right and two to the left. Comfortable turning speed was calculated by dividing the length of the CM path the subject used for the turn by the time taken for the turn. CM path length was measured from entry into the Gate 2 area to the crossing of a line 0.5 m laterally beyond the edge of the walkway.

For the main trials, subjects were told to start walking at a comfortable pace and, if the lights on a pole lit, to turn as quickly as possible into the gate whose forward limit was to be the stance leg and the swing/left foot to be horizontally not more than one-fourth of the subject’s average stride length from crossing the right leg. Variations in gait speed and pattern dictated that this window be used in defining the gait-phase criterion. In the mean, at the times used for turn signal initiation, the left foot had passed the right leg in 20% of the trials. In 80% of the trials, the left foot was either behind or just crossing the right leg. Had all turns been made without delay at turn signal initiation, then all turns to the right and to the left, respectively, would have been turns to the stance and to the swing leg side. Because the turns were in fact delayed from turn signal initiation times, there was only a tendency for this to be the case.

Available response time (ART), the interval from pole lights being lit until the CM marker would have passed forward of the designated gate, was affected by starting position, walking speed, and CM location at turn signal initiation, with the last two not fully controllable. In each turn trial, at the time appropriate to having the turn made at the specified gate, the software predicted in real time what the ART would be, based in part on the subject’s average walking speed. If ART was predicted through this method to be within 10 ms of nominal ART and the gait-phase criterion was also met, lights were switched on automatically and signaled the turn to the subject.

Actual ART and walking speed were computed immediately post-trial. If actual ART was within 10% of nominal ART and actual walking speed was within 10% of the subject’s average comfortable walking speed, trial data were accepted. Otherwise, the trial was repeated at the end of the test session. On average, fewer than 10 trials per subject needed to be repeated. Nominal ART data will be reported here, but post-hoc checks showed actual ART to be approximately evenly scattered about nominal ART.

For all but the first five subjects, the main trials consisted of 160 trials in the same fixed, initially randomized sequence. Those trials included 40 straight-walk, dummy trials during which no lights appeared, 40 turn-trials at Gates 1 or 4, and 80 turn-trials, 20 at each of four ART (375, 450, 600, and 750 ms), at Gates 2 or 3. These trials included equal numbers of right (nominally, to the stance leg side) and left (swing leg)-side turns, and Gate 2 and Gate 3 turns. Only data from Gate 2 and Gate 3 turns were used in the analysis of the results to be reported, but subjects were not aware of this.

For the first five subjects tested (3 YF, 1 YM, and 1 OF), 100 straight-walk or Gate 1 or Gate 4 turn-trials and 100 Gate 2 or Gate 3 turn-trials were conducted, 20 each at ART of 300, 450, 600, 750, and 900 ms. Those subjects had zero success in turning as prescribed at 300 ms ART and complete success at 900 ms ART. Thus, the four turn-trial ART listed above were used for all of the remaining subjects.

During the test session, subjects were given a 1 min rest after every 20 trials and a 10 min rest after 80 trials. Subjects were also invited to take additional rest periods whenever they felt that was needed.

**Failure criteria.** — A turn was considered successful if none of these failures occurred: (a) Forward Momentum Arrest Failure, in which the CM passed forward of the designated turn gate; (b) Pole Contact Failure, in which the subject contacted a light pole; (c) Turn Path Failure, in which the subject stepped outside of the lateral limits of the

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**Figure 2.** Schematic diagram of placement of infrared diodes on the subject. The concentric circles represent the six diode pairs. A and B represent the double pair used to locate approximately the whole-body center-of-mass. C represents the pairs (one per side) just superior to the kneecaps and D the pairs (one per side) just superior to the shoe tongues.
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turn path; and (d) Slow Turn Failure, in which the actual average speed of the turn was slower than that subject’s average comfortable turning speed by more than 30%.

Data analysis. — The rate of success (RS) for each ART and side-of-turn was calculated for each subject as the number of successful trials divided by 10, since a total of 10 trials were conducted for each ART and side-of-turn. Mean values and standard deviations of RS were calculated for each ART across age, age/gender, and age/gender/side-of-turn groups. For the first five subjects, a presumed RS at an ART of 375 ms was obtained by linear interpolation of the RS at 300 ms, which was uniformly zero, and 450 ms ART. To check whether inclusion of those five subjects had any substantial effect on study outcomes, an additional analysis was made that excluded those five subjects.

Repeated measures ANOVA was used to examine the significance of differences in RS with ART, age, gender, side-of-turn, and the interactions among these four factors. RS/ART relationships were interpolated by least-squares fitting the nonlinear logistic regression curve

\[ RS = 100 \times \frac{\exp(b_0 + b_1 \times ART)}{1 + \exp(b_0 + b_1 \times ART)} \]

to the discrete RS data points for each of the subject groups.

Practice and fatigue effects. — For each subject, comfortable gait speeds and RS were checked by repeated measures ANOVA for significant increases (practice effects) or decreases (fatigue effects) over the test session. Gait speed was compared between the initial and final 10 main trials. RS was compared for each ART between the first and the second half of the main trials.

RESULTS

Types of failure. — Across all subjects and conditions, there were 3,300 trials during which sudden turns at Gates 2 or 3 were attempted. Failure to turn as instructed occurred in 1,174 of these. Of these, 1,163, or 99% of the failures, were Forward Momentum Arrest Failures. There were 11 Pole Contact Failures among three YF, one YM, three OF, and one OM; one of the YF failed in four trials and all the others in only one. No subject failed any trial by Turn Path or Slow Turn Failure, nor did any subject fall during the trials.

Effects of available response time (ART) on rate of success (RS). — RS significantly \((p < .001)\) increased with increasing ART. Both age groups had mean RS lower than 50% for ART of 375 ms and mean RS higher than 95% for ART of 750 ms (Table 2, Figure 3).

Effects of age on RS. — Young subjects had a significantly higher RS than old for each ART (Table 2, Figure 3). At 450 ms ART, RS was 67% for young and 27% for old, for example. The logistic regression analyses suggested that, to achieve an RS of 50%, young would have needed 408 ms ART, and old 523 ms ART. Those analyses suggested that for RS from 30 to 95%, old subjects on average would have needed 112 ms additional ART to achieve an RS equal to that of the young.

Effects of gender on RS. — In both age groups, males had a higher RS than females for every ART (Table 2). The gender difference was larger for the old than for the young. The regression analyses suggested that, for RS from 30 to 95%, OF would have needed 66 ms additional ART to achieve an RS equal to that of OM, and YF would have needed 37 ms additional ART to achieve an RS equal to that of YM.

Other results. — Substantial variability in RS was found among all four age and gender groups (Table 2, Figure 4). No significant difference in RS was found between turns to the right and turns to the left side. However, an Age X Side-of-Turn interaction approached significance \((p = .064)\). YA had higher (by 9, 7, -2, and 2% for 375, 450, 600, and 750 ms ART, respectively) mean RS for right turns than left turns, while OA did not show a systematic difference in this regard. There was a significant \((p < .001)\) ART X Age interaction. No other significant interactions were found among the four factors. No substantial changes in outcomes were found when the first five subjects were excluded from the analyses, so all results reported here include those five subjects.

No significant fatigue effects were evident. Across all subjects, comfortable walking speed did not change signifi-

Table 2. Effect of Age, Gender, and Available Response Time on Mean Rates of Success (Mean ± SD)

<table>
<thead>
<tr>
<th>ART (ms)</th>
<th>YF (%)</th>
<th>YM (%)</th>
<th>OF (%)</th>
<th>OM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>375</td>
<td>33.0 ± 28.4</td>
<td>38.8 ± 21.3</td>
<td>0.5 ± 2.2</td>
<td>11.5 ± 19.0</td>
</tr>
<tr>
<td>450</td>
<td>60.0 ± 32.9</td>
<td>74.2 ± 21.9</td>
<td>12.0 ± 19.6</td>
<td>41.5 ± 37.9</td>
</tr>
<tr>
<td>600</td>
<td>92.8 ± 10.9</td>
<td>97.1 ± 5.7</td>
<td>70.5 ± 21.8</td>
<td>85.5 ± 19.3</td>
</tr>
<tr>
<td>750</td>
<td>97.6 ± 7.1</td>
<td>100.0 ± 0.0</td>
<td>96.0 ± 7.5</td>
<td>97.0 ± 4.7</td>
</tr>
</tbody>
</table>

Notes: ART = available response time. Y = young, O = old, F = female, and M = male subjects. By repeated measures ANOVA: \(p < .001\) for significant ART difference; \(p < .001\) for significant age difference; \(p = .022\) for significant gender difference; \(p < .001\) for significant ART X Age interaction; \(p = .020\) for significant ART X Gender interaction; \(p = .064\) for Age X Side-of-Turn interaction.

Figure 3. Mean rate of success in turning as instructed for each available response time. The regression curves fit to the data points for the young (YA, solid line) and old (OA, dashed line) groups are shown. Plus-and-minus one standard error is shown for each data point.

No significant fatigue effects were evident. Across all subjects, comfortable walking speed did not change signifi-
correspond to young adults needing to recognize the object approximately 523 ms before they would reach it. At a walking speed of 1.3 m/s, these needed response times correspond to young adults needing to recognize the object approximately 53 cm, and old adults, approximately 68 cm ahead of reaching it.

This additional 115 ms warning time, or its corresponding additional 15 cm warning distance, that healthy old adults compared to young need for a reasonable probability of success in suddenly making a turn may seem small. However, the consequence if one is old of not having that additional warning time and distance is not small: for example, with a 450 ms available response time, RS was 67% for YA but only 27% for OA.

Ninety-nine percent of the 1,174 failures to turn as instructed resulted from apparent inability to fully arrest forward momentum within the available time. We also found gender differences in abilities to turn suddenly. To achieve the same RS, young and old females need approximately 40 and 70 ms longer ART than males of corresponding age.

Our subjects apparently were highly motivated to succeed in their assigned task, as evidenced by the lack of any significant decline in comfortable walking speed or in rates of success across the 160 main trials.

This study had a number of limitations. The old subjects were in good physical condition, as evidenced by their self-reported activities and a comfortable walking speed that was no different from that of the young subjects. This limits the generalizability of study findings to broader populations of elderly. Essentially, responses were explored at only one gait speed and at only two phases of the gait cycle. Although subjects did not know fully whether they would be signaled to turn, they must eventually have surmised that there was a 75% probability of that happening. They did not know exactly where they might be asked to turn, but they knew the general area in which that could occur. On the other hand, they did not know in advance to which side a turn would have to be made.

Ikeuchi et al. (6) studied ground reaction forces in six young male adults during starts, turns, and stops made at a known location while walking. They did not control the time available in which to complete these tasks. Patla et al. (7) studied abilities of young adults to make unexpected turns. Half of their trials were straight walk trials, compared to one-fourth in the present study. However, they used only one turning point in their study, compared to the four of the present study, so that their subjects could better anticipate where and approximately when the cue to turn might be given. In the Patla et al. study, subjects freely chose to turn to the swing leg side or to the stance leg side. Most of their subjects preferred swing-leg to stance-leg-side turns. Patla et al. did not test the effects of side-of-turn on RS. Their three cue times (at heel strike, and 100 and 300 ms after heel strike) correspond approximately to our ART of 600, 500, and 300 ms. They found RS of 88, 80, and 40%. Our regression analysis suggests that the RS for our young adults would have been 95, 80, and 14%, so the two studies are in reasonable agreement in this respect, despite these differences in study details.

Avoidance of an obstacle by a sudden turn is apparently a more difficult task than avoidance by stepping over it, when that can be done. Perhaps this is not surprising in light of the different biomechanical requirements of the two responses. Chen et al. (4) studied the effects of age and ART on abilities to avoid stepping on suddenly appearing gait-path obstacles of zero height. They found that young and old adults needed ART of 270 and 290 ms to achieve an RS of 50%. Through their regression analysis, they found the old would have
needed approximately only 30 ms additional ART to achieve the same overall RS as young adults. Comparing present results with those of Chen et al., to achieve a 50% RS in turning away from an obstacle compared to avoiding stepping on it, young and old adults needed 408 and 523 ms ART, and the age difference in needed ART for the same overall RS was 112 ms. Moreover, the largest age-group RS difference that Chen et al. found over any of the ART they examined was approximately 8%, while in the present study that difference was 40%. Thus, the decline with age in abilities to meet the challenge is more pronounced when suddenly turning than when suddenly altering stepping pattern.

Turning suddenly and unexpectedly is a complex and time-critical task that involves rapid perception, rapid strategy planning, and rapid motor execution, during all of which whole body balance must be maintained. Study findings show that delays as small as 50 to 100 ms in sensing the need for, planning, and executing a turn will significantly lower the probability of completing that turn so that barrier contact does not occur. Healthy old adults, and old females in particular, are apparently less able to meet these challenges than are young adults. Perhaps these findings explain to a small degree the high rates of fall injuries among old compared to young adults and the twice-as-large fall injury rates among old females compared to old males (8–10).

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