Age Differences in Using a Rapid Step To Regain Balance During a Forward Fall

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Background. Earlier studies showed that healthy old adults have substantially reduced abilities to develop joint torques rapidly. We hypothesized that this age decline would reduce abilities to regain balance once a forward fall is underway. The present study examined whether aging in fact reduces ability to regain balance by taking a single, rapid step upon release from a forward lean.

Methods. Ten young (mean age 24.3 yr) and ten old (72.8 yr) healthy males were released from a forward-leaning position and instructed to regain standing balance by taking a single step forward. Lean angle was successively increased until a subject failed to regain balance as instructed. Lower extremity motions and foot-floor reactions were measured during the responses. Total response time was divided into reaction, weight transfer, and step times.

Results. At small lean angles, responses of old subjects were similar to those of the young. However, the mean maximum lean angle from which old could regain balance as instructed was significantly smaller than that for young (23.9 vs 32.5 deg, $p < .0005$). Within each age group, maximum lean angle correlated strongly with weight transfer time and step velocity.

Conclusions. Substantial age-related declines in the ability to regain balance by taking a rapid step exist among healthy adults when the time available for recovery is short. The source of the decline seems largely to lie in the decrease with age of maximum response execution speed rather than in the sensory or motor programming processes involved in response initiation.

THE high incidence of fall-related injuries among the elderly is well recognized, but little is known about the mechanisms underlying those injuries. For example, do old have more difficulty than young adults in restoring standing balance after starting to fall? Chen (1) showed through computer simulation studies that once a fall starts, the maximum rate of torque development in lower extremity joints is likely to be an important determinant of whether that fall can be arrested and standing balance regained by taking a step. Thelen et al. (2) showed that torque development in the ankles is significantly slower in old compared to healthy young adults. If other body joints show similar age decrements in the rapid development of torque, then even healthy old adults may exhibit diminished abilities, compared to young adults, to step rapidly in order to arrest an ongoing fall. To test this concept, we measured the largest forward body lean angle from which young and old healthy male adults, when suddenly released, could regain standing balance by taking a single, rapid step. Our null hypothesis was that this maximum forward lean angle is not significantly different in old compared to young male adults. In the expectation that this hypothesis would be rejected, we also measured step kinematics and push-off forces to gain further insights into the sources of any age differences found in the maximum lean angle. Stepping responses of healthy young adults during a forward fall have been studied previously (3,4, for example), but not those of healthy old adults.

METHODS

Subjects. — Ten young (age range 20 to 30 yr) and ten old (67 to 75 yr) healthy male subjects participated (Table 1). Males rather than females were recruited to decrease the risk of osteoporosis-related fractures in the Old. Potential subjects were asked which foot they would use to kick a ball. Only subjects reporting that they would use their right foot were recruited, so that motion measurement required viewing the subject only from his right side. Data on subject heights and weights and measures of lower body anthropometry were gathered.

Young were recruited among University staff and students. Old were independent community-dwelling members. All Old underwent a standardized medical history and physical examination that focused on musculoskeletal and neurological items (5,6). All denied a history of significant musculoskeletal, neurological, or otological disease. Nevertheless, upon careful screening, two Old were found to have sustained lower extremity fractures in the distant past, but neither had residual pain or subsequent loss of range of motion. Five Old noted infrequent pain in the lower extremities or back in the past, but were not symptomatic at the time of the test. Physical examination found that four Old had decreased or asymmetric lower extremity reflexes, and one had slight position sense loss at the big toe. All Old subjects were physically active, exercising or taking part in strenuous

Table 1. Subject Data

	Young			Old		
	Age (yr)	Height (cm)	Body Mass (kg)	Age (yr)	Height (cm)	Body Mass (kg)
Mean	24.3	173.9	72.8	71.3	176.8	74.7
Max	30	179	80	75	187	85
Min	20	167	62	67	173	65

activities, including aerobics, walking, biking, and yard work, at least three times per week.

Experimental protocol. — A horizontal lean-control cable attached to the back of a padded pelvic belt supported the subjects while they kept their bodies approximately straight in a forward leaning posture (Figure 1). Subjects were not required to keep their heels in contact with the floor. The magnitude of the forward lean was controlled by adjusting the cable length until a load cell attached to the cable indicated that it supported a specified percentage of the subject's body weight. This was done because supported body weight fraction could be measured more precisely than presumed lean angle and did not require that "straight" be defined for all body segments. The lean angle corresponding to this amount of weight support was calculated post-hoc from measured data (Appendix), assuming the body to consist of one rigid link.

Forward falls were induced by releasing the lean-control cable after a random time delay, following the scheme of Do et al. (3). Subjects were instructed to attempt to regain standing balance by taking a single step forward with their right foot. Subjects also wore a safety harness suspended from an overhead track. The length of the harness suspension cable was adjusted similarly for Young and Old, so that the subject's hands could not contact the floor in the event of a failure to restore balance upon lean-control cable release. An incorporated load cell monitored harness suspension cable loads during balance recovery.

In the first set of trials (Small Lean Trials), the subject attempted to recover balance following three releases each at three lean-control cable loads: 15, 20, and 25% of body weight. These trials were presented in sets of three fixed, initially randomized trial blocks. No practice trials preceded these. In the second set of trials (Maximum Lean Trials), the supported weight was successively incremented by 5% of body weight to determine the maximum lean angle from which the subject could successfully regain balance with a single step. Trials were terminated if the subject failed twice at a given percentage of supported body weight or if he refused further trials.

Failure to recover balance as instructed was defined to occur when the subject at any time placed 18.5% or more of his body weight on the safety harness support (Support Use Failure), or took a second right leg step of any kind or a left leg step whose length exceeded 30% of his body height (Multiple Step Failure). The harness load criterion was chosen to distinguish between the small loads exerted on the

Figure 1. Computer-assembled subject configurations during the initial stages of the response. **Left:** Before release. **Center:** Shortly after release. **Right:** At approximately the time of right foot liftoff. The horizontal belt attached to the lean-control cable is behind the subject, at waist level. The vertical safety harness support cable, some of the infrared-emitting diode markers, and portions of the forceplates can be seen.

harness track by forward movement of the subject from the large loads that accompanied an assisted single-step recovery. Post-hoc visual inspection of the data records showed that the 18.5% body weight criterion did discriminate between these two situations. The left leg step length criterion accommodated subjects who took small steps with their left foot to maintain their balance laterally while taking not more than one step with their right foot. Responses were video-taped and reviewed to determine the characteristics of any additional steps taken. The approximate amount of trunk flexion that subjects used during balance recovery was visually observed during the trials and spot-checked during reviews of the videotapes.

Instrumentation. — Data on body segment motions, foot/floor reactions, and lean-control and harness-support cable loads were collected. Data collection was synchronized and simultaneously initiated 500 msec prior to subject release. Data were sampled at 100 Hz for 3 sec during each trial.

As already noted, load cells monitored lean-control and harness-suspension cable loads. Foot/floor reaction forces and moments on each side were measured (for the right leg, only during the initial response period) using two Advanced Medical Technology (Watertown, MA) six-component forceplates. Step landing time was detected using a switch-plate placed on the floor forward of the subject.

An Optotrak (Northen Digital, Waterloo, Ontario) optoelectronic motion analysis system was used to measure body segment motions. Infrared emitting diodes were placed on the right leg over the lateral metatarsal, heel, lateral maleolus, lateral fibula head, and lateral epicondyle; and on the thigh, midway between the knee and greater trochanter. Four diodes were placed on the medial side of the left leg: at the medial metatarsal, heel, medial maleolus, and medial tibial head. Two diodes placed on the right shoulder and temple tracked trunk and head motion. Three diodes fixed to

the forceplates were used to specify the location of these devices in the data set.

Data and statistical analysis. — The total time from subject release to landing of the right foot on the switchplate was divided into reaction time, weight transfer time, and step time (Figure 2). Reaction time was defined as the interval between release of the lean-control cable and the initial increase in the vertical force under the subject's right foot. Weight transfer time was the interval between reaction time and right foot liftoff. Step time was the interval between liftoff and landing of the right foot. The marker placed over the right metatarsal was used to calculate the length of the step taken. Step velocity was the average forward velocity of the foot, defined as step length divided by step time. All of these quantities were identified through software, rather than manually.

Only data from the subject's final trial at each lean angle were included in the analyses of the results. For the Small Lean Trials — those with lean-control cable loads of 15, 20, and 25% of body weight — a two-way ANOVA was used to examine the significance of differences with age and lean magnitude in step length, step velocity, reaction time, weight transfer time, and step times. For the Maximum Lean Trials, *t*-tests were used to determine whether there was a significant age-group difference in the mean largest lean angle from which subjects could restore balance as instructed. Within each age group, reaction times, transfer times, step times, step lengths, and step velocities were linearly regressed with maximum lean angles.

RESULTS

Small leans. — For the set of trials with lean-control cable loads of 15, 20, and 25% of body weight, both Young and Old typically completed their initial step within 500 msec after release (Figure 3). The time to step landing among both Young and Old included a mean reaction time of 57 to 71 msec, a mean weight transfer time of 234 to 268 msec, and a mean step time of 151 to 178 msec (Table 2).

Reaction times were independent of lean angle. These times were 8 to 10 msec longer in Old than in Young, with the age difference statistically significant ($p < .005$). Weight transfer times were independent of age but decreased with increasing lean magnitude (Table 2). This decrease bordered ($p = .053$) on statistical significance, and weight transfer time continued to decrease as lean angle was increased during the Maximum Lean Trials (Figure 3).

Mean step lengths ranged from 67 to 89 cm, corresponding to 38 to 51% of body height. Step lengths were significantly dependent on lean magnitude ($p < .05$, Table 2). Young tended to take slightly longer steps than old subjects at any given lean angle, but this difference was not statistically significant. Mean step velocities ranged from 409 to 526 cm/sec. Step velocities were independent of age, but increased significantly with lean magnitude ($p < .00001$, Table 2).

Maximum leans. — All Young were able to regain balance with a single step from lean-control cable loads of up to
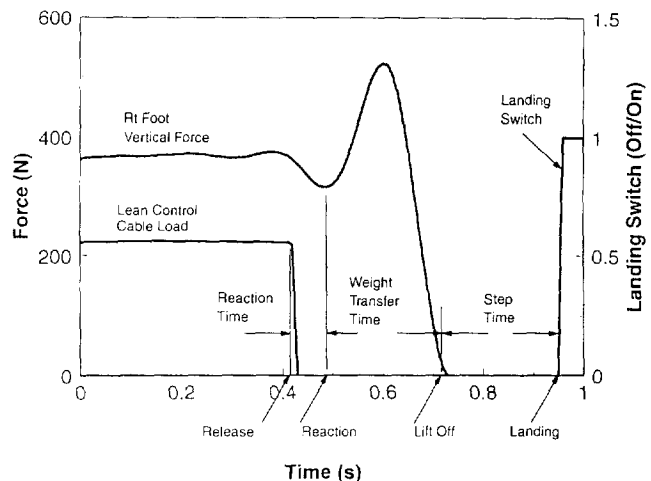

Figure 2. Sample time history of the lean-control cable load, the vertical force on the right (stepped) foot, and step-plate switch closure. The derived response time interval measures are also shown.
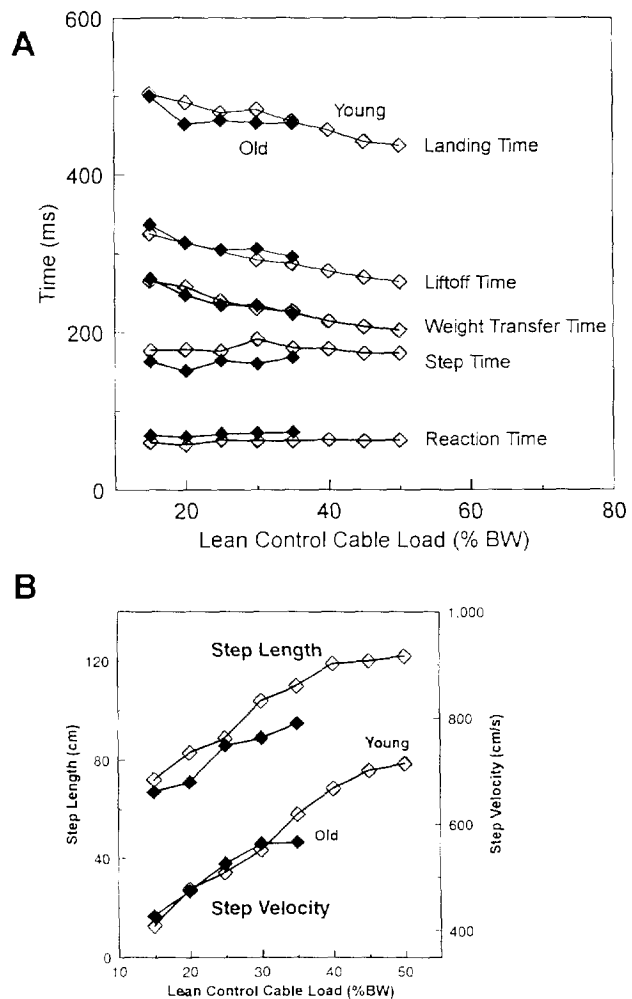

Figure 3. Mean response time measures (A), and mean step length and velocity (B) for Young and Old as a function of initial lean magnitude. Some of the response time measures presented in (A) are interdependent, but are provided for ease of interpretation of the results.

Table 2. Small Leans: Mean Values of Response Parameters

Lean (% BW)	Reaction Time* (msec)		Transfer Time** (msec)		Step Time (msec)		Step Length† (cm)		Step Velocity‡ (cm/sec)	
	Young	Old	Young	Old	Young	Old	Young	Old	Young	Old
15	60	69	265	268	177	163	72	67	409	427
20	57	67	258	247	178	151	83	71	477	474
25	63	71	240	234	176	164	89	86	509	526

Notes: Data on standard deviations available from authors. Table 4 provides the conversions between the percent body weight supported and the lean angle. Significance of differences tested by ANOVA. Only leans of 15, 20, and 25% of body weight (BW) were included in the statistical analysis, since these are the only leans from which all subjects were able to restore balance as instructed.

*p < .005 for age effects.

†p < .05 for lean effects.

‡p < .00001 for lean effects.

**p < .053 for lean effects.

35% of body weight. Some Old were unable to regain balance at lean loads greater than 20% of body weight (Figure 4). The mean maximum lean angle (Table 3) from which Old recovered under the imposed conditions was significantly smaller than that for Young (23.9 vs 32.5°, $p <$ .0005). All Young exhibited Support Use Failures, while nine of the ten Old exhibited Multiple Step Failures. The remaining old subject refused further trials before failing.

Within each age group, maximum lean angle showed good inverse correlation with weight transfer time ($r = -.87$ for Young, and $-.73$ for Old) and with step time ($r = -.84$ and $-.50$). Maximum lean angle also showed good direct correlation ($r = .84$ and $.75$) with step velocity. Reaction time and step length were generally not well correlated with maximum lean angle (Table 3).

Lean angles. — The calculated mean equivalent lean angles (Appendix) corresponding to the imposed lean-control cable loads ranged from 13.3 to 30.0° among the Old and 13.5 to 43.0° among the Young (Table 4).
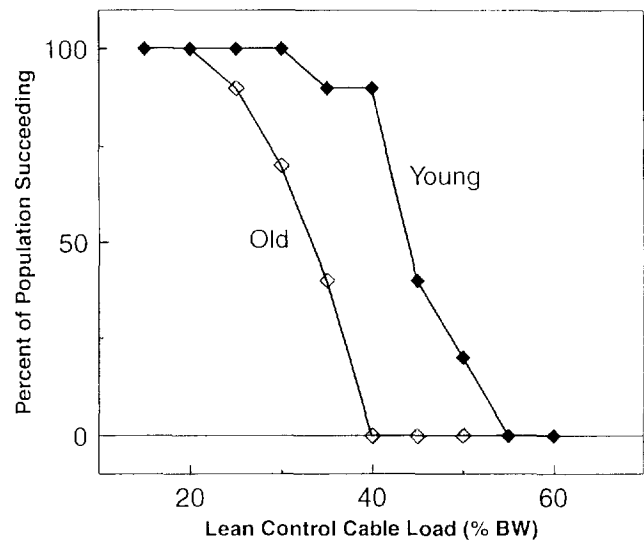
DISCUSSION

This study investigated the effects of age on the ability of healthy males to regain balance by taking a rapid step in response to being released from small and large forward leans. Among the study's salient findings, the responses of the two age groups at small lean angles differed little, but the maximum initial lean from which the old adults could recover as instructed was considerably smaller than that for young adults. This observation implies that substantial age differences in abilities to restore balance may only be elicited among healthy adults in the face of a pronounced challenge.

While age differences in reaction times during the Small Lean Trials were statistically significant, they seem not to have been biomechanically significant. Reaction times were only approximately 10 msec longer in the Old than in the Young, while the total time required for completing a step was on the order of 500 msec. Moreover, within the age groups, reaction times were not strongly correlated with maximum lean angle.

The results suggest that the source of the age-related decline in recovery abilities lies largely in the decrease with age of the maximum speeds with which the lower extremity

Figure 4. Percent of young and old subjects who succeeded in regaining balance with a single step at the various lean-control cable loads.

Table 3. Maximum Leans: Mean Values of Response Parameters

	Young	Old	Correlation Coefficient	
			Young	Old
Max lean angle (deg)	33 (4)	24* (4)		
Reaction time (msec)	65 (1)	68 (9)	−.51	.01
Wt. transfer time (msec)	221 (16)	237 (19)	−.87	−.73
Step time (msec)	176 (25)	167 (27)	−.84	−.50
Step length (cm)	120 (8)	91 (11)	−.01	.09
Step velocity (cm/sec)	689 (78)	548 (63)	.84	.75

Notes: Mean values of the maximum lean angle from which balance was regained with a single step, the corresponding reaction time, weight transfer time, step time, step length, and velocity of the step used to regain balance at that largest lean are shown. The coefficients of linear correlation of these variables with the maximum lean angle within each age group are shown. Standard deviations in parentheses. Significance of age-group difference determined by independent *t*-test.

*p < .0005 for age effect.

Table 4. Conversion Between Percent of Body Weight Supported by the Lean Control Cable and Mean Equivalent Lean Angles

Cable Load (% BW)	Lean Angle (deg)	
	Young	Old
15	13.5	13.3
20	17.3	17.8
25	20.6	21.5
30	22.7	24.4
35	26.7	27.8
40	30.8	30.0
45	35.7	
50	38.0	
55	43.0	

segments could be moved, rather than in the sensory or motor programming processes involved in response initiation. In the Small Leans Trials the performances of Young and Old were essentially the same except for the small age difference in reaction times. Physical laws dictate that as lean angle increases, the time available for balance restoration decreases. As the lean angle was increased, neither Old nor Young changed their reaction times by any notable amount. Both groups of subjects instead increased the speed of their body segment movements (Figure 3). Subjects decreased their weight transfer times and increased their step velocities and step lengths. The decreasing slopes of the weight transfer time, step velocity, and step length vs lean magnitude curves (Figure 3) suggest that both age groups eventually reached a lean magnitude from which they were incapable of further speeding of response execution and were therefore unable to recover balance as instructed. Old subjects reached this threshold at smaller lean magnitudes than did the Young. Apparently, mean maximum execution speed for the Old was substantially lower than that for the Young.

As already noted, all Young ultimately exhibited Support Use Failures, while 9 of the 10 Old ultimately exhibited Multiple Step Failures. This difference in types of failure apparently occurred partially as a result of increased trunk flexion among the Young. Direct visual observations and spot videotape reviews of trunk motion during the trials confirmed this difference in trunk flexion angles, although no objective measurements of trunk motion were made. The age differences in use of trunk flexion may have resulted from age differences in voluntary selection of balance recovery strategies or from the decreased abilities of the Old in the rapid development of the hip torques needed to flex the trunk and the right thigh during balance recovery.

We examined balance recovery abilities using a well-controlled but artificial situation. Subjects were aware that they would soon undergo a fall and they knew in which direction it would occur. The subjects had no forward momentum when the fall began, as would be the case in a trip while walking. Our initial conditions of no momentum diminished the risk for accidents and avoided having to deal with the control of gait speed and gait phase during tripping. Moreover, we prescribed the balance recovery strategy that subjects were to attempt. Luchies et al. (7) found in experi-

ments related to the present ones that young subjects generally preferred to take single steps, and old subjects generally preferred to take multiple steps to recover balance upon a perturbation of standing posture.

Differences in subject motivation seem an unlikely source of the age differences found in this study. At the larger leans, both Young and Old clearly were highly motivated to step as rapidly as possible. Perhaps the decision to initiate a step could have been delayed slightly at the smaller leans and a successful recovery still made, but such delays in response time were not evident at any of the lean angles.

We do not know to what extent additional practice in restoring balance might have changed the outcome of this study. Although we did not allow the subjects any practice trials, the statistical analyses of the Small Lean Trials used data only from the last successful trial by a subject. Moreover, subjects performed the nine Small Lean Trials before they attempted the Maximum Lean Trials.

Only 60 to 70 msec elapsed between the subjects being released and their initiation of a push-off force at the floor. These reaction times are comparable to those found in an earlier study of forward falls (3), but are considerably shorter than lower extremity voluntary effort reaction times, which are on the order of 200 msec (2,8). Do et al. (9) found that the onset of myoelectric activities occurred approximately 60 msec following release from a forward leaning posture. We presume that similar short latency active muscle contractions led to the short reaction times found in this study. In addition, substantial muscle contraction forces and muscle stretches had to be present prior to release in order to hold the body straight in the forward lean configurations. These contractions and stretches may have also influenced the timing of the push-off forces following release.

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Appendix

Calculation of the Equivalent Initial Lean Angle

The angle of whole body lean (ϕ), between the vertical and the line from the whole body center-of-mass to the transverse axis of the ankle joints, that corresponded to the measured lean-control-cable load (P) was calculated post-hoc for each subject and trial. That calculation involved the following additional measured quantities: Subject body weight (W) and height (h), ankle height (k), horizontal distance (e) from the ankles to the line of action of the vertical support force (also W), and height (d) of the lean-control cable above the ankles.

Equilibrium of sagittal plane moments about the ankles requires that these quantities relate through

$$P d = W [(\alpha h - k) \sin \phi - e]$$

where α, the proportion of body height at which the whole body center of mass lies, was taken to be .60, based upon the data of Winter (10). With values for all other quantities known, ϕ was calculated from this equation.