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Effects of Age on Balance Assessment Using Voluntary and Involuntary Step Tasks

Carl W. Luchies,[1,2] Dennis Wallace,[1,3] Ryan Pazdur,[4] Sarah Young,[4] and Alice J. DeYoung[5]

[1]Center on Aging, University of Kansas Medical Center, Kansas City.
[2]Department of Mechanical Engineering, University of Kansas, Lawrence.
[3]Department of Preventive Medicine, University of Kansas Medical Center, Kansas City.
[4]Department of Physics and Engineering
and [5]Department of Nursing, Hope College, Holland, Michigan.

Background. Taking a step while standing and modifying a step while walking are two strategies often used to maintain balance when balance disturbances are encountered during activities of daily living. This study investigated whether performance on an involuntary step task, which is assumed to be a surrogate for fall recovery abilities, was comparable to performance on a voluntary step task.

Methods. The performance of a voluntary and an involuntary step task was measured in healthy young adult (mean age 21 years) and healthy elderly adult (mean age 68 years) female subjects. Subjects stepped as fast as possible in the direction of a minimally destabilizing lateral waist pull (voluntary step task), or they responded naturally to a large destabilizing lateral waist pull (involuntary step task). The effects of age, task, and their interaction on the primary outcome variables of step foot liftoff time, landing time, step length, and step height were examined.

Results. In the voluntary step task, the older adults, compared to the young, required significantly more time to lift their foot (Young: 307 msec; Elderly: 424 msec). In the involuntary step task, the elderly were as quick as the young in lifting their foot (Young: 322 msec; Elderly: 335 msec). The young lifted their foot at about the same time for the two tasks. The elders, on the other hand, lifted their foot significantly earlier in the involuntary step task, compared to the voluntary step task (Vol: 424 msec; Invol: 335 msec).

Conclusions. A voluntary step task underestimates the ability of healthy elderly adults to respond quickly when large destabilizing balance disturbances are encountered.

THE significance of injurious falls in elderly people has been well documented as exemplified by the frequency of falls (1,2), fractures due to falls (3–5), health costs due to falls (6,7), and fear of falling leading to a reduction in activities of daily living (8). Effective methods to identify those at risk of falling are needed to reduce the risk of injurious falls. Reduced strength, impaired balance, and the use of medications have been identified as fall risk factors (5,9–12), and interventions have been developed to reduce these factors (13). The ability to respond quickly, appropriately, and effectively to large destabilizing balance perturbations has been shown to be affected by the aging process. For example, Luchies and colleagues (14) found significant age-group differences in the step lift time, step landing time, step distance, step height, and the use of a single versus multiple step strategy in response to backward disturbances. Thelen and coworkers (15) determined that elderly, compared to young adults, had approximately 25% smaller maximum lean angles from which they could successfully regain balance using a single step response. The "change-in-support" strategy often used to maintain upright stance was recently reviewed (16).

Previous studies have determined the effects of age on involuntary postural responses. Investigations, however, have not adequately explored the effect of age on voluntary responses. In addition, the relationship between voluntary stepping and involuntary stepping has not been explored. Does performance on voluntary tasks adequately characterize fall recovery abilities, or do the involuntary conditions often associated with falls have to be present to measure these abilities directly? This study investigated voluntary and involuntary step tasks in healthy young and elderly subjects.

Methods

Subjects.—Thirteen healthy young adult (YA: mean age 21, SD = 2.5 yrs) and 11 healthy elderly adult (EA: mean age 68, SD = 4.1 yrs) women were tested. Mean height and weight were comparable in the two groups (Table 1). Each subject gave her informed consent as approved by Hope College's Human Subject Review Board. Young adult subjects were recruited from the student body of Hope College and physical therapy students from Grand Valley State University. Elderly adult subjects, living independently in the community, were recruited from a low impact aerobics fitness program sponsored by the Evergreen Commons Senior Center, Holland, Michigan. A detailed health history was obtained from all subjects, and a physical examination, based on standardized cardiovascular (17), musculoskeletal (18), and neurological (19) items, was conducted on all elderly subjects by a registered nurse in consultation with a physician-geriatrician.

Subjects were excluded from the two groups if history (and in the elderly adults, physical examination) revealed significant positive findings for head trauma, otologic, neurologic, or cardiovas-

Table 1. Subjects' Anthropometric Data

	Young	Elderly
Number (*n*)	13	11
Mean age (yrs)	20.9 (2.5)*	68.0 (4.1)
Age range (yrs)	16–25	62–74
Mean height (cm)	170.3 (6.9)	165.8 (6.8)
Mean body mass (kg)	62.0 (5.4)	69.0 (14.6)

* Standard deviations in parentheses.

cular disease; visual impairment not correctable with lenses; musculoskeletal impairments; neurologic impairments; or a history of symptoms of vertigo, lightheadedness, unsteadiness, or falling.

Of the 11 elderly subjects tested, some revealed subtle abnormalities during the health history or physical examination. Five subjects reported occasional osteoarthritic symptoms, four subjects reported two affected joints, and one subject reported four affected joints. Two demonstrated minimal bilateral proximal weakness of the lower extremities (dorsal plantar flexion), with scores of 4+/5 on a scale of 0 (no muscle contraction) to 5 (maximal resistance without fatigue). Four reported diagnoses of mild hypertension controlled with medication. Ten subjects had Mini-Mental State Exam scores of 30; one had a score of 29.

Despite the subtle abnormalities revealed in history and physical examination of the elderly adults, all subjects participated in a low impact aerobics class held for 1 hour 3 days/week at the senior center or in the pool at Hope College. In addition, all subjects exercised on a regular basis at home (such as vigorous walking or biking up to 4 miles/day), maintained their own homes (including yard work), and participated in many community volunteer programs that required substantial strength and stamina (e.g., kitchen cooks, waitressing, private duty nursing, commercial drapery making).

Tasks.—Data were collected on two tasks related to recovery from falls: a voluntary step task and an involuntary step task. The stimulus used in this study was a normalized lateral displacement at the waist, produced using a weight and pulley system that was similar to the Postural Stress Test (20). For the voluntary step task, subjects were instructed to step as fast as possible in the direction of a minimally destabilizing lateral waist pull, which was chosen small enough so that a sway response could have been used to restore balance. For example, subjects were instructed to step to the right with their right foot when they felt a small pull to the right. For the involuntary step task, subjects were instructed to respond naturally to a large waist pull, which was chosen large enough so that a step response was necessary for all subjects to restore balance.

For the involuntary step task, the subjects were not instructed as to whether or not to step, nor were they instructed with which foot to step, nor as to how many steps they should take, even if they asked for further guidance. For each task, five left pulls and five right pulls were introduced in a predetermined random sequence unknown to the subject and replicated across all subjects. Each subject performed 10 trials of the voluntary task, followed by a short rest, then 10 trials of the involuntary task. Prior to the beginning of each task, several practice trials were used to acquaint the subjects with the test procedures.

The subject stood upright, looking straight ahead, arms folded across the chest, and bare feet placed in a standardized stance position (21). The standardized stance position consisted of a 20 cm lateral foot spacing, measured between the lateral side of the foot on an axis intersecting the left and right medial malleolus; and a 25° foot angle, measured between a tangential line along the lateral edge of the foot and the sagital plane. A warning light illuminated randomly 0.5–3.0 seconds prior to the pull onset. The subject wore a suspended safety harness designed to safely arrest any major fall but not to interfere with the responses under observation. The subject wore a second harness around the waist incorporating padded blocks adjusted to provide secure contact with their anterior-superior iliac spines for transmission of the disturbing force to the body.

Lateral right and left pulls were produced using electronically released weight and cable systems, which were designed to allow the subject to sway freely prior to the release of the weight. One set of solenoids released the weight, and another set of solenoids released a cable cleat which grabbed the cable. To avoid audible cues to the direction of the disturbance, both lateral left and right weights were released simultaneously. The weight dropped for the voluntary and involuntary tasks was 20% of the subject's body weight. An electronic controller simultaneously triggered the data acquisition and weight release systems, although a short delay (approximately 300 msec) was introduced before the dropping mechanism released the weight so that prestimulus conditions could be determined. The large and small waist pull distances were 8.7% and 1.3% the waist height, respectively, corresponding to a 5.0° and 0.75° equivalent disturbance angle as defined by Luchies and colleagues (14). The average amount of the subsequent drop and the corresponding horizontal waist displacement averaged 1.75 cm and 9 cm for the small and large waist pull, respectively. For each task, all subjects experienced essentially the same disturbance independent of their age group (Table 2). The peak force magnitude and impulse strength were independent of age group, although the force duration was slightly longer for the EA, compared to the YA (YA = 281 ± 9.0 msec, EA = 310 ± 9.4 msec, $p = .024$). The two tasks differed for the peak force magnitude (vol: 28.7 ± 2.7 N [Newton], invol: 183.0 ± 7.5 N, $p < .001$), impulse strength (vol: 4.5 ± 0.3 Ns [Newton-seconds], invol: 37.9 ± 1.5 Ns, $p < .001$), and force duration (vol: 263 ± 8.2 msec, invol: 328 ± 7.1 msec, $p < .001$).

Experimental measures.—Data on body segment landmark motions, foot/floor reactions, myoelectric activity, and waist harness cable forces were collected. Data collection was synchronized with data simultaneously collected for 2 seconds for each trial. Body segment landmark motions were measured using an Optotrak (Northern Digital, Waterloo, Ontario) optoelectronic motion analysis system, which tracked the locations in three dimensions of infrared emitting diodes (IREDS). The IREDS were placed to track the motions of the right and left foot (midline calcaneus) and the waist harness (midline, posterior side). The marker locations were sampled at 200 Hz. The six components of the reactions exerted by the floor on the left and on the right foot were measured using two Advanced Medical Technology (Watertown, MA) forceplates. The forceplates were surrounded by switchplates, which were used to de-

tect step foot landing time if the subject stepped off the forceplates. A load cell, attached to each drop mechanism, measured the time history of the lateral waist pull force. The forceplate, switchplate, and load cell data were sampled at 2000 Hz. Myoelectric data were measured in the right and left tibialis anterior (TA) muscles using Motion Control (Salt Lake City, UT) bipolar surface electrodes. The myoelectric data were sampled at 2000 Hz. All responses were also videotaped.

Data analysis.—Data from all trials were fully processed using MATLAB (Mathworks, Natick, MA). All kinematic, forceplate, and load cell data were digitally filtered using a second order Butterworth filter with a 6 Hz cutoff frequency and with forward and backward reflection to minimize initial and final-time artifacts. Phase shift was eliminated by using forward and backward passes. The myoelectric data were full wave rectified about the mean.

The disturbance onset time, left and right TA myoelectric onset time, step foot liftoff time, and step foot landing time were determined. Because this study focused on the initial step taken, the analysis only considered the TA onset time in the leg used for the initial step. The TA onset time and step foot liftoff and landing times are reported relative to the disturbance onset time. The waist pull force was quantified in terms of its duration, peak force, and force-time integral (impulse strength). The disturbance onset time was determined using a threshold method on the waist pull force. When the waist pull force exceeded a 5 Newton (N) force and then dropped below a 5 N force, the disturbance onset and ending time, respectively, were established. The TA onset time was determined based on a threshold method. Based on predisturbance TA myoelectric activity, the quiet TA myoelectric activity mean and standard deviation were determined. The onset time of the TA myoelectric activity was established when the myoelectric activity exceeded the prestimulus mean + 3 standard deviations and maintained this level for 15 out of the subsequent 30 samples similar to the method described by DiFabio (22). The step foot liftoff time was determined using the vertical force component on the corresponding forceplate. When the vertical force component was less than 5 N, the step foot liftoff time was established. The step foot landing time was determined using either the corresponding vertical force component or the switchplate signal. Step foot landing time was established when either the vertical force exceeded the 5 N threshold, or when the switchplate signal switched from a low to a high state, whichever came first. Step height and step length were determined based on the heel kinematic data.

The weight shift time was defined as the time between the TA onset time and the step foot liftoff time in the leg used to take the initial step (motor time + time to develop enough muscular force to lift the step leg). The step duration time was defined as the time between step foot liftoff and step foot landing time for the initial step.

Table 2. Unadjusted Mean Disturbance Characteristics for Each Task

	Task	
	Voluntary Step	Involuntary Step
Force duration (msec)		
Young	250 (36)*	311 (32)
Elderly	276 (43)	344 (36)
Peak force (Newton)		
Young	29 (9)	175 (16)
Elderly	28 (12)	191 (49)
Impulse strength (Newton-seconds)		
Young	4.3 (1.3)	35.5 (3.9)
Elderly	4.7 (1.9)	40.4 (9.5)

* Standard deviations in parentheses.

Statistical analysis.—The focus of the statistical analysis was on estimating the effect of age group (young vs old), task (voluntary vs involuntary), and their interaction on the primary outcome variables of step foot liftoff time, landing time, step length, and step height of the first step. TA onset time, weight shift time, and step duration were used to investigate primary outcome variables. Initially, parameter means and standard deviations were calculated for each age group to characterize the subject sample, which was grouped by age, task, and step direction. Separate linear mixed models then were developed for each outcome to examine the effects of age group, task, and their interaction controlling for possible confounders using model building strategies described by Kleinbaum et al. (23) and Neter et al. (24). The linear mixed model approach is a generalization of the analysis of covariance (ANCOVA) approach implemented with any standard linear models or analysis of variance (ANOVA) package, but it provides more flexibility in accounting for within-subject correlation than does repeated measures ANOVA (25). Although these seven outcomes are related statistically and functionally, a straightforward modeling strategy that examined each outcome individually rather than a more complicated multivariate modeling strategy was selected as the best mechanism for gaining insight into the relationship of voluntary and involuntary tasks in this initial study. Furthermore, because this initial sample has relatively small sample sizes, the statistical analyses are considered to be descriptive rather than inferential with an emphasis on estimating the magnitude of effects. *P* values are presented descriptively as a measure of the strength of evidence that the effects found did not occur simply by chance, and they should be interpreted cautiously given the number of outcomes examined. *P* values from the models are based on an approximate *F* test characterized in the literature as the best test statistic for such models, with follow-up pairwise comparisons based on Wald-type tests with the Tukey-Kramer adjustment for multiple comparisons (26). Unless otherwise noted, results presented are model-adjusted means and are presented as mean estimate ± *SE*. For comparison, unadjusted results are presented in Table 3. All analyses were performed with SAS Version 6.11 software (SAS Institute, Cary, NC).

RESULTS

First-step liftoff time.—The liftoff time exhibited a Group × Task interaction manifested in a difference in liftoff time in the two age groups in the voluntary task but not in the involuntary task and a task effect that differed in the EA but not in the YA. In the voluntary step task, the EA, compared to the YA, required 38% more time for liftoff (YA: 307 ± 25 msec, EA: 424

Table 3. Unadjusted Mean Step Kinematic Parameters

	Task			
	Voluntary Step		Involuntary Step	
Liftoff time (msec)				
Young	307	(50)*	323	(59)
Elderly	425	(116)	334	(50)
Landing time (msec)				
Young	507	(60)	461	(89)
Elderly	629	(102)	508	(62)
TA onset time (msec)				
Young	93	(13)	97	(18)
Elderly	127	(28)	120	(26)
Weight transfer time (msec)				
Young	234	(35)	234	(45)
Elderly	311	(118)	228	(26)
Step duration (msec)				
Young	206	(53)	221	(175)
Elderly	210	(55)	195	(85)
Step length (cm)				
Young	17.2	(10.0)	23.7	(11.9)
Elderly	20.9	(8.6)	27.1	(12.7)
Step height (cm)				
Young	3.2	(0.9)	5.1	(2.0)
Elderly	3.4	(1.3)	6.1	(2.0)

* Standard deviations in parentheses.

± 26 msec, $p = .007$). In the involuntary step task, the EA were as quick to initiate the step as the YA (YA: 322 ± 16 msec, EA: 335 ± 16 msec, $p = 0.9$). In the EA, the liftoff time for the voluntary step task, compared to the involuntary step task, required 27% more time (vol: 424 ± 26 msec, invol: 335 ± 16 msec, $p = .002$). In the YA the liftoff time was similar for the two tasks.

First-step landing time.—Similarly, the landing time exhibited a Group × Task interaction: the two age groups differed substantially in landing time in the voluntary task but not in the involuntary task with a task effect found in the EA but not in the YA. In the voluntary step task, the EA, compared to the YA, required 23% more time for landing (YA: 507 ± 24 msec, EA: 628 ± 25 msec, $p = .003$). In the involuntary step task, no evidence was found of a difference in the EA and YA landing time (YA: 463 ± 22 msec, EA: 507 ± 23 msec, $p = 0.5$). In the EA, the landing time for the voluntary step task, compared to the involuntary step task, required 23% more time (vol: 628 ± 25 msec, invol: 507 ± 23 msec, $p < .001$). In the YA, the landing time was similar for the two tasks.

TA onset time, weight shift time, and step duration time.—Analysis of the TA onset time, weight transfer time, and step duration time was used to determine the source of any differences observed in the liftoff and landing times for the first step. A group effect was found in the TA onset time, with the EA having a longer latency compared to the young (YA: 95.3 ± 5.6 msec, EA: 123 ± 5.8 msec, $p < .001$). The weight shift time demonstrated the same trend as the liftoff and landing time. A Group × Task interaction was found with an age-group effect found in the voluntary task but not in the involuntary task and a task effect found in the EA but not in the YA. In the voluntary step task, the EA, compared to the YA, required 32% more time for weight shift (YA: 234 ± 24 msec, EA: 310 ± 25 msec, $p = .13$). In the involuntary step task, the EA were as quick to shift their weight as the YA (YA: 233 ± 10 msec, EA: 229 ± 11 msec, $p = .99$). In the EA, the weight shift time for the voluntary step task, compared to the involuntary step task, required 35% more time (vol: 310 ± 25 msec, invol: 229 ± 11 msec, $p = .009$). In the YA, the weight shift time was similar for the two tasks. No age-group or task effects were found in step duration.

Step height and length.—A task effect was found in the step height. The mean step height in the involuntary task was 70% larger compared to the voluntary task (vol: 3.3 ± 0.2 cm, invol: 5.6 ± 0.4 cm, $p < .001$). Also, a Direction × Group interaction was found in the step height. The YA in the right direction used a smaller step height compared to the YA in the left, the EA in the right, and the EA in the left direction (YA: right 3.7 ± 0.4 cm, left 4.7 ± 0.4 cm; EA: right 4.8 ± 0.4 cm, left 4.7 ± 0.4 cm, $p < .001$). A substantial task and direction effect was found in the step length, with a small Task × Direction interaction. The involuntary, compared to the voluntary, resulted in an initial step 34% larger in length (vol: 19.0 ± 1.9 cm, invol: 25.5 ± 2.5 cm, $p < .001$). The step lengths differed by direction in the involuntary task (right: 24.2 ± 2.5 cm, left 26.7 ± 2.5 cm, $p = .004$), but not in the voluntary task (right: 18.9 ± 1.9 cm, left 19.2 ± 1.9 cm, $p = 0.8$).

Learning effects on step kinematics.—Learning effects were found on some of the step kinematics. Liftoff time decreased only in the involuntary task by 10 ± 3.4 msec per trial ($p = .004$). The landing time decreased by 9 ± 2.7 msec per trial the same for the two tasks ($p < .001$). Step length decreased 0.4 ± 0.2 cm per trial ($p = .04$).

Discussion

This study demonstrates that the performance of a voluntary step taken as fast as possible in response to a minimally destabilizing disturbance does not reflect the ability to take a time-critical involuntary step in response to a large destabilizing balance disturbance in healthy elderly adults. While young and elderly adults performed equally well in the involuntary step task, the response delay in the elderly adults on the voluntary task was due primarily to prolonged weight shift times and, to a lesser extent, to a small increase in muscle activation latency. In order to accurately capture the ability of healthy elderly adults to respond quickly in a fall situation, their balance must be challenged enough to exhibit protective balance recovery strategies.

Our data suggest that the elderly group, despite the instructions to step as fast as possible, chose to take more time for a voluntary step compared to the time used to take a step when their balance was challenged. The subjects also used a shorter step length and a smaller step height in the voluntary task, compared to the involuntary task. This discrepancy may be due to their desire to maintain a performance reserve in order to provide options during their response.

Within each task, the increase in the TA onset time (premotor) with increasing age suggests an increase in the motor planning time with increasing age, which is consistent with earlier findings (26). Within each group, the TA onset time was similar across the two tasks, suggesting that the two tasks required similar cognitive processing even though the voluntary step task

fosters conscious planning while the involuntary step task requires subconscious planning. Alternatively, this could be an artifact of the experimental design. The subject's prior knowledge of the disturbance magnitude, although not the direction, may have resulted in some preplanning of the step response. It is also possible that the small waist pull used in the voluntary step task evoked an involuntary TA balance response. Assessing balance in the laboratory using repeated unexpected balance disturbances remains a challenge.

The similar weight shift times across the two groups in the involuntary step task may have resulted from the use of similar peak rate-of-force development levels for weight shift. In an isolated ankle task, maximal strength and the maximum rate of torque development decreased with increasing age (27). Data were not collected to determine if either group approached their maximal strength or maximum rate of torque development in either task. In the elderly group, the increased weight shift time in the voluntary, compared to the involuntary step task, may suggest that the elderly adults chose a lower rate of force development when taking a volitional step unrelated to balance recovery. The large standard deviation in the elderly group's weight shift time in the voluntary step task may have resulted from a more variable selection in the motor plan used to achieve step leg liftoff.

In our earlier study of posterior waist perturbations (14), the elderly subjects, compared to the young, utilized responses resulting in earlier step liftoff times; this was not observed in the current study. The difference in the control strategy used to respond to lateral, compared to other disturbance directions, needs further study. Further study is needed to determine if the differences observed between the voluntary and involuntary step tasks in the lateral direction are typical of other directions.

In this study, the subjects maintained their arms crossed in front of them. Further study is needed to understand how the upper extremities are used for balance recovery. Further study is needed to assess step responses in elderly subjects with a history of falling and/or with age-related diseases. The learning effect found, which resulted in decreased step liftoff and landing times in the involuntary step task, may suggest an intervention for older adults who have slowed step responses, but this will require further study.

The major finding of this study is that the performance of a voluntary step task does not reflect the ability to take a step quickly in response to destabilizing balance disturbances in healthy elderly adults. The age-group differences observed in the voluntary step task, which were absent in the involuntary step task, were due to increases in the weight shift time and the TA onset time. The neurological mechanisms underlying involuntary actions may not be the same as those required for volitional responses. The assessment of both may improve the identification of the source(s) of balance impairment, resulting in a more focused treatment plan.

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Address correspondence to Dr. Carl W. Luchies, Mechanical Engineering, The University of Kansas, 3013 Learned Hall, Lawrence, KS 66045-2234. E-mail: luchies@ukans.edu

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