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Human Factors: The Journal of the Human Factors and Ergonomics Society 2010 52: 3 originally published online 13 May 2010
DOI: 10.1177/0018720810368541

Effect of Practice on Stepping Movements Onto Laterally Compliant Raised Structures: Age Differences in Healthy Males

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Objective: The aim of this study was to examine effects of practice and age on step-up movements onto raised structures. **Background:** Falls from laterally compliant structures, such as stepladders, often cause injuries in elderly persons. Although age differences in step-up movements onto raised structures with unexpected structural compliance have been reported, practice effects of such movement control have not been investigated. **Method:** Movement behavior of 20 healthy adults (10 young and 10 older males) was measured while they stepped up onto a raised structure with no compliance (i.e., rigid) (C_0), a small amount of mediolateral compliance (C_1), or greater mediolateral compliance (C_2). The conditions C_0, C_1, and C_2 were presented in three sets of six fixed-order trials with step-up movements performed at a comfortable speed. Practice effects in step-up behavior were examined by comparing data within each trial block with the use of repeated-measures ANOVA. **Results:** Practice significantly reduced the stepping duration (*T*s) needed to complete the step-up movement ($p < .001$). With practice, older males reduced their lateral oscillations 26% to 40% for C_1 and C_2, whereas the corresponding results for young males lay between 8% and 17%, respectively. The age difference in *T*s decreased across six consecutive trials but remained significant, especially on the structure with greater compliance. **Conclusion:** With practice, both young and elderly men adapted their stepping behavior to the presence of lateral structural compliance, but it is noteworthy from a fall-injury prevention perspective that the elderly men required more trials to do so. **Application:** Designers and users of raised structures, such as stepladders, should be aware of the age difference of people using such structures and should minimize the structure compliance when designing them.

INTRODUCTION

Falls from ladders or similar structures cause injuries across the age spectrum. However, injurious falls tend to be more frequent and serious in older populations. According to the U.S. Bureau of Labor Statistics (2001), more than 15% (or 122 cases in 2001) of occupational fatal falls are from ladders. Because ladders are also used at home, the absolute number of ladder falls is even greater (Bjornstig & Johnsson, 1992; Faergemann & Larsen, 2000). Men are three times more likely than women to experience fall injuries from ladders or scaffolds in nonoccupational settings, and the incident rate increases significantly with age, irrespective of gender (Faergemann & Larsen, 2000, 2001). In 2002, ladder-related injuries and deaths of people ages 65 and older cost the United States more than US$2.6 billion (U.S. Consumer Product Safety Commission, 2005). Because fall-related injuries from ladders tend to be more severe than falls at ground level (Cohen & Lin, 1991; Muir & Kanwar, 1993; Partridge, Virk, & Antosia, 1998), there is a need to prevent as many such falls as possible, especially by elderly persons.

Ladder falls have several different accident patterns. When people use stepladders, lateral falls are the most common accident type (Bjornstig & Johnsson, 1992). A previous simulation study

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has quantified the feasible range of a user's whole-body center-of-mass (COM) state (position and velocity) for which the user's weight could be transferred in the mediolateral (ML) direction without tipping a rigid stepladder. The study has showed that the lateral stability of a human standing on a rigid stepladder is most sensitive to the height of the tread from the ground on which the user stands, where the stance foot is positioned relative to the side rail, and the lateral inclination of the ladder (Yang & Ashton-Miller, 2005).

By definition, no stepladder can be completely rigid under load; all such ladders therefore have structural compliance to a greater or lesser extent. In this article, we consider structural compliance in the lateral direction (corresponding to the human user's ML direction), which might place greater demands on users' balance capabilities to stabilize the mechanical system comprising the human and the compliant structure on which he or she stands.

In a previous study of people's stepping behavior in response to an unexpected structural compliance, we found significant effects of structural compliance and age on movement control (Yang & Ashton-Miller, 2006). Furthermore, healthy adults needed more time to complete the stepping movement onto a raised structure with unexpected lateral structural compliance; this time increased with increasing structural compliance, and older males (OM) compared with young males (YM) needed significantly more time to recover balance in the frontal plane on the laterally compliant raised structure.

Although these findings are important, it is also relevant to know whether any practice effects occur during repeated exposures to the same structural compliance. In addition, it is unknown whether advancing age affects these responses. It is evident that healthy adults are able to adaptively adjust their responses to reduce the risk of falls from moving surface perturbations within five repeated exposures to the same postural perturbation (McIlroy & Maki, 1995; Pavol, Runtz, Edwards, & Pai, 2002). However, adaptation of movements in response to the self-induced perturbations caused by stepping onto a laterally compliant structure has not yet been studied.

TABLE 1: Mean Age, Body Height, and Body Mass of Participants in Two Equal Groups of 10

	Age (in years)	Body Height (in cm)	Body Mass (in kg)
Young males (YM)	26.0 (2.5)	168.5 (1.7)	71.4 (11.6)
Older males (OM)	72.2 (2.6)	168.7 (4.3)	69.1 (8.1)

Note. Standard deviations shown in parentheses. No significant body height ($p = .92$) and body mass ($p = .74$) differences between YM and OM.

The purpose of this study, therefore, was to investigate how participants adapt to the presence of lateral structural compliance while repeatedly stepping onto a raised structure, such as a short stepladder or stool. To do this, we analyzed multiple trial data from Yang and Ashton-Miller (2006), an experimental study in which only first trial responses had been analyzed and reported. We tested the primary null hypotheses that there are (a) no significant adjustments in stepping behavior in the repeated exposures (six trials) to stepping up onto the same laterally compliant structure, (b) no age differences in these adjustments, and (c) no effects of structural compliance on the step-up movement adjustments. The secondary null hypotheses are that after practice (five repeated exposures), there is (a) no age difference in the stepping movements and (b) no effect of structural compliance on stepping movements.

METHOD

A secondary analysis was performed of the data of 20 participants from a previous study (Yang & Ashton-Miller, 2006). The participant information and experimental protocols are described in the following paragraphs.

Participants

The data of 10 YM and 10 OM participants (see Table 1) were analyzed. All participants were healthy, community-dwelling individuals. Body height, mass, and anthropometry of major

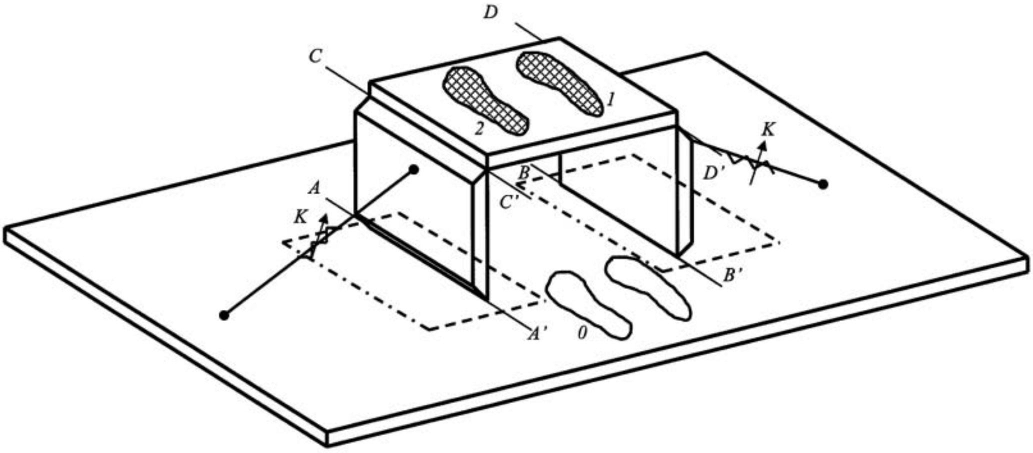

Figure 1. Schematic of the experimental apparatus showing the hidden lateral metal springs, which could be covertly added or subtracted to adjust structural compliance. The lines A–A', B–B', C–C', and D–D' are axes of rotation. The dashed lines denote the location of force plates underneath the platform; the crosshatched foot shapes represent the F-Scan pressure sensor mats, and the open foot shapes denote the starting position for each foot. Reprinted from "Stepping Onto Raised, Laterally Compliant Structures: A Biomechanical Study of Age and Gender Effects in Healthy Adults," by B.-S. Yang and J. A. Ashton-Miller, 2006, *Human Factors*, *48*, p. 209. Copyright 2006 by the Human Factors and Ergonomics Society. Reprinted with permission.

body segments (torso, legs, and feet) were measured for each participant. No participant reported having a balance disorder or acrophobia. A nurse clinician, under the supervision of a physician-geriatrician, screened all the elderly participants to exclude those with any physical impairment, such as neurological or musculoskeletal injuries, that could obstruct movement control or postural balance. The institutional review board approved all test procedures, and all participants gave written consent to the study.

Experimental Protocol

Participants wore a full-body safety harness mounted from an overhead track by an adjustable-length fetter. They were asked to stand barefoot on firm ground, with arms crossed in front of the chest, and then to step forward and up onto a structure 7 in. (0.178 m) high at a self-selected comfortable speed. The raised, hinged structure was built on a large platform (2.2 × 1.0 m), and steel springs on each side provided all of the lateral resistance to movement (see Figure 1). The ML compliance of the structure, measured at the level of the upper surface, could then be covertly adjusted by altering the number of steel springs to one of three values: a small amount of compliance ($C_1 = 1 \times 10^{-4}$ m/N), greater compliance ($C_2 = 2 \times 10^{-4}$ m/N), and rigid ($C_0 < 10^{-5}$ m/N). The value of C_1 was determined from the mean value of five less-than-1-year-old commercial stepladders at the height of the second rung from the bottom with the stepladder fully opened. The C_2 condition provided 2 times the compliance of C_1.

Six trials were then performed in each compliance condition. Trial order was six C_0, six C_1, and six C_2 trials interspersed to prevent participants from knowing when a change occurred. For example, for one participant, the trial order was six C0, six C0, six C1, six C0, six C0, and six C2 trials; for another participant, the order was six C0, six C1, six C0, and six C2 trials. Participants were also asked to perform three additional stepping trials onto the rigid structure, each with two different stepping speeds ("50% comfortable speed" and "as fast as possible").

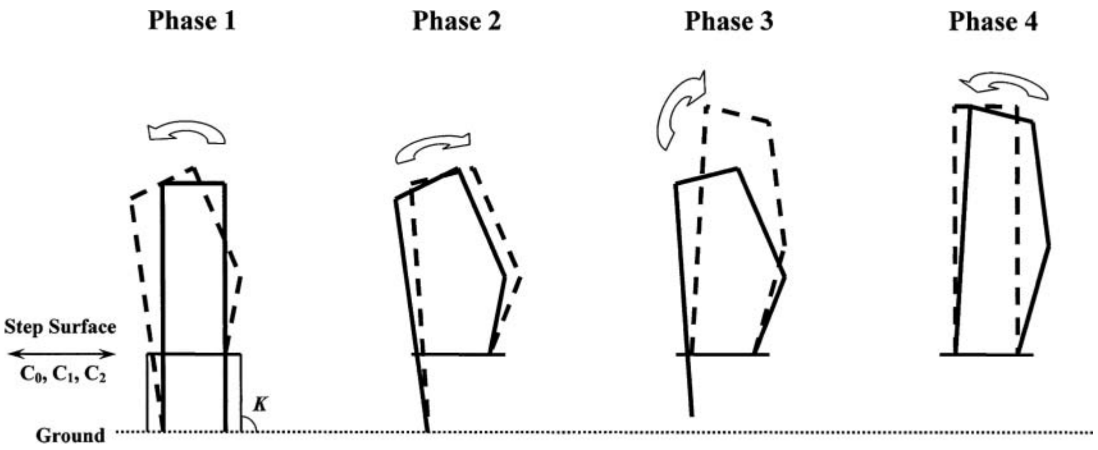

Figure 2. Four phases of forward stepping movement onto a raised structure in the frontal plane. The thick solid lines illustrate initial leg states, and broken lines illustrate final states of each phase. Arrows indicate the directions of weight transfer. Reprinted from "Stepping Onto Raised, Laterally Compliant Structures: A Biomechanical Study of Age and Gender Effects in Healthy Adults," by B.-S. Yang & J. A. Ashton-Miller, 2006, *Human Factors*, *48*, p. 210. Copyright 2006 by the Human Factors and Ergonomics Society. Reprinted with permission.

Body segment and structure kinematics were recorded with the use of an Optotrak 3020 (Northern Digital, Canada) at 100 Hz with 10 infrared-emitting markers on bony landmarks of the participant's dorsal surface (one marker each on lateral aspect of the shoulder, inferior angle of the 10th rib, center of rotation of leg in frontal plane, lateral side of knee, and center of rotation of ankle in frontal plane). Two AMTI (Advanced Mechanical Dynamics, USA) OR-6 force plates were mounted underneath the platform to measure ground reaction forces at 100 Hz.

The whole-body COM location was calculated from three body segments: head-arm-torso and two legs. This estimation of COM position in the ML direction was verified for each participant from force plate center of reaction data with the participant in three static postures: upright stance, upper body flexed laterally (10° to 15°) to the right, and upper body flexed laterally to the left. Two F-Scan (Tekscan, USA) foot pressure sensors, each larger than the foot size, were placed on the upper surface of the structure to capture, at 100 Hz, the time history of the normal reaction force under each foot.

The kinematic and kinetic data were digitally low-pass filtered with the use of a fourth-order Butterworth filter (Matlab®) with a cutoff frequency of 10 Hz; the data passed forward and backward through the filter to minimize phase shift.

Phases of Stepping Movement

To compare the stepping movement among participants and trials, four movement phases were defined (see Figure 2; Yang & Ashton-Miller, 2006):

Phase 1: Weight-transfer preparation phase: begins at the first lateral COM movement and ends at the first contact of the lead foot with the raised structure (*t1*).

Phase 2: Bipedal weight-transfer phase: from *t1* to the time of the trailing foot's losing contact with ground (*pf*). Participant could use this phase to identify structural compliance and adjust movement strategy onto the raised structure.

Phase 3: Unipedal support phase: begins at *pf* and ends at the first contact of the trailing foot with the raised structure (*t2*).

Phase 4: Bipedal recovery phase: begins at *t2* and ends at lateral weight-transfer rate between two legs returning to the value of quiet stance (mean ± 2 standard deviations).

TABLE 2: Descriptions/Abbreviations for the Dependent Parameters

Parameter	Description
T_{II}	Duration in Phase 2 (normalized by duration in Phase 1)
T_{III}	Duration in Phase 3 (normalized by duration in Phase 1)
T_{IV}	Duration in Phase 4 (normalized by duration in Phase 1)
T_{IVa}	Duration for reaching control of lateral COM movement in Phase 4 normalized by duration in Phase 1 (lateral COM state < threshold of mean ± 2 standard deviations of COM displacement during quiet standing)
T_s	Duration of completing one step-up movement (from Phase 1 to Phase 4)
v_p	Lateral COM velocity at trailing-foot push-off (normalized by BH)
v_{zf}	Vertical foot placing velocity of trailing foot in Phase 3, normalized by BH (negative sign: downward)
R_p	Vertical push-off force underneath trailing foot (normalized by Body Weight)
d_{III}	Maximum structural lateral displacement in Phase 3 (normalized by BH)
d_{IV}	Maximum structural lateral displacement in Phase 4 (normalized by BH)
e_{IIa}	Lateral COM excursion in Phase 2 before reaching the maximum lateral weight transfer rate (normalized by total lateral COM excursion in the stepping movement)

Note. COM = center of mass; BH = body height; BM = body mass.

Data and Statistical Analyses

Kinematic and kinetic parameters (see Table 2) in the four movement phases (see Figure 2) were used to compare the practice (repeated exposure) effects, and the effects of age and structural compliance in and after repeated exposures, on the stepping movements. The primary parameters investigated here are the time to complete the step-up movement (Ts, the sum of T_I through T_{IV}), which demonstrates the difficulty of the task, and the maximum lateral displacement of the structure in Phases 3 and 4 (d_{III} and d_{IV}), which is a measure of the stability of the system. Because the time used in Phase 1 (T_I) was positively correlated with the stepping speed that participants used in the three rigid-structure tasks ("comfortable speed," "50% comfortable speed," and "as fast as possible") and T_I is not significantly different across test conditions ($p = .24$), six trials ($p = .76$), or age groups ($p = .13$), all time durations are presented as multiples of time duration spent in Phase 1 in each trial to minimize intertrial and interparticipant variances in the self-selected speed. Human body and structure displacements and velocities were normalized by each participant's body height; weight-transfer magnitude and rate, by each participant's body weight.

Repeated-measures ANOVAs were performed in SPSS to examine the main effects and interactions of practice (differences between six consecutive trials), structural compliance, and age (differences between participant groups) on stepping movements. To examine the effects of structural compliance and age on stepping movements after practice (in the sixth trial), additional repeated-measures ANOVAs were used to compare data of the sixth trial in each test condition and participant group. Because significant age effects ($p < .001$) on stepping behavior were found in the first trial, which involved laterally compliant structures (Yang, 2004; Yang & Ashton-Miller, 2006), we are interested in whether elderly men are able to compensate for the age effects on this movement control after several consecutive trials, or "practice"; that is, are there any differences between the step-up movement of OM after practice (movement in their sixth trial) and that of YM before practice (movement in their first trial)? Therefore, post hoc repeated-measures ANOVAs were performed to compare movement parameters of the first trial of YM with those of the sixth trial of OM.

A p value less than .05 was considered statistically significant unless otherwise noted. As mentioned earlier and found in our previous

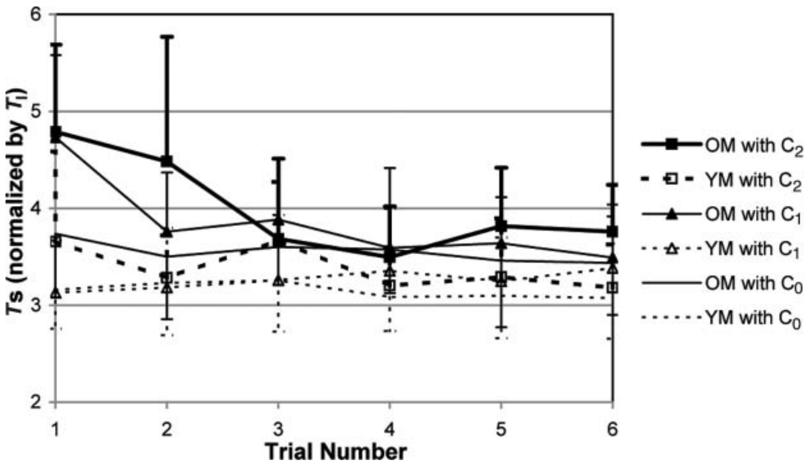

Figure 3. Mean values (error bars represent standard deviations) of total duration (*T*s), normalized by T_I, of one stepping movement onto the raised structure with three values of structural compliance (C_0, C_1, and C_2) in six consecutive trials each. Significant practice (trial) effects were found ($p < .001$). The *p* value for age effects was $p < .01$, and that for the interaction between age and practice was $p < .01$. OM = older males; YM = younger males.

study, three outcome parameters, *T*s, d_{III}, and d_{IV}, were significantly associated with the performance of the investigated step-up movements (Yang & Ashton-Miller, 2006); we performed Bonferroni correction (with significance level of $p < .05/3$) in the tests of these three primary variables. The other dependent variables, therefore, were studied here as the secondary variables (without Bonferroni correction) to investigate the details of movement control mechanism in each condition.

RESULTS

Effects of Practice

Practice significantly ($p < .001$) affected *T*s, the stepping duration, onto the compliant structures (C_1 or C_2) of healthy male adults, especially for OM. Figure 3 shows the changes of *T*s in each participant group under three test conditions. For both groups, *T*s on the rigid structure (C_0) was not significantly affected by practice. When OM stepped onto the compliant structures, *T*s decreased significantly with practice, whereas *T*s for YM decreased slightly for C_2 from the first to sixth trials but remained similar for C_1 within six consecutive trials.

Because most movement adjustments (see Figure 3) occurred on the compliant structures (C_1 or C_2), Table 3 presents data before and after practice of the stepping movements onto those two compliant structures only. The effects of age ($p < .01$) and interaction effects between practice and age ($p < .01$) were both significant. Within two (for C_1) or three (for C_2) trials, OM significantly reduced the total duration of the stepping movements onto the laterally compliant structures. *T*s of OM decreased 21% from the first to second trials for C_1 and 23% from the first to third trials for C_2, whereas YM showed a relatively smaller decrease (15%) in *T*s from the first to sixth trials for C_2 but no large changes for C_1.

Of the four phases of the stepping movement, there were significant effects of practice on duration only in Phases 2 and 4 (see Figures 4 and 5). In the bipedal weight-transfer phase (Phase 2) in the sixth compared with the first trial, YM spent 36% and 25% more time for C_1 and C_2, respectively, whereas OM spent 13% and 7% more time for C_1 and C_2, respectively ($p < .05$). In the balance recovery phase (Phase 4) in the sixth compared with the first trial, OM spent 51% and 40% less time for C_1 and C_2, respectively, whereas YM spent 32% less time for C_2 but 8% more time for C_1 ($p < .001$). OM also showed significantly more practice effects than did YM in the “controlling lateral COM movement” subphase in Phase 4, the duration

TABLE 3: Mean Parameter Values in the First and Sixth Trials in Each Participant Group on the Compliant Structures

		C_1				C_2			
		YM		OM		YM		OM	
Parameter		Trial 1	Trial 6	Trial 1	Trial 6	Trial 1	Trial 6	Trial 1	Trial 6
T_{II}	#, **, $$	0.45 (0.09)	0.61 (0.17)	0.53 (0.13)	0.60 (0.20)	0.56 (0.22)	0.70 (0.21)	0.54 (0.13)	0.58 (0.15)
T_{III}	**, !!	0.42 (0.08)	0.40 (0.16)	0.45 (0.06)	0.53 (0.07)	0.42 (0.10)	0.34 (0.14)	0.38 (0.10)	0.44 (0.10)
T_{IV}	##, **, +, !!	1.27 (0.54)	1.37 (0.48)	2.75 (0.79)	1.36 (0.39)	1.68 (0.73)	1.14 (0.43)	2.88 (0.81)	1.74 (0.46)
T_{IVa}	##, **, ++, !	0.74 (0.28)	0.72 (0.25)	1.66 (0.71)	0.92 (0.39)	1.03 (0.72)	0.99 (0.57)	1.89 (0.62)	1.19 (0.27)
T_s	##, **, ++, !!	3.13 (0.54)	3.38 (0.53)	4.73 (0.85)	3.49 (0.55)	3.66 (0.93)	3.18 (0.45)	4.79 (0.90)	3.76 (0.48)
v_p	** (1/sec)	0.108 (0.030)	0.109 (0.031)	0.087 (0.024)	0.092 (0.032)	0.051 (0.052)	0.051 (0.049)	0.043 (0.050)	0.065 (0.035)
v_{zf}	##, **, + (1/sec)	–0.497 (0.093)	–0.422 (0.088)	–0.535 (0.131)	–0.431 (0.078)	–0.566 (0.141)	–0.526 (0.141)	–0.690 (0.211)	–0.531 (0.145)
R_p	+	0.320 (0.112)	0.376 (0.118)	0.384 (0.157)	0.390 (0.211)	0.336 (0.061)	0.352 (0.165)	0.454 (0.155)	0.371 (0.160)
d_{III}	##, **, %	0.0050 (0.0012)	0.0043 (0.0013)	0.0055 (0.0013)	0.0040 (0.0013)	0.0126 (0.0037)	0.0104 (0.0041)	0.0147 (0.0034)	0.0109 (0.0029)
d_{IV}	#, **	0.0038 (0.0010)	0.0035 (0.0011)	0.0050 (0.0015)	0.0032 (0.0014)	0.0113 (0.0048)	0.0104 (0.0060)	0.0152 (0.0055)	0.0091 (0.0022)
e_{IIa}	**	0.473 (0.116)	0.423 (0.121)	0.382 (0.119)	0.412 (0.110)	0.472 (0.125)	0.441 (0.150)	0.359 (0.103)	0.329 (0.121)

Note. Repeated-measures ANOVAs on six trials, three test conditions, and two groups. No units appear because all parameters are normalized. Standard deviations shown in parentheses. C_1 = structure with smaller mediolateral compliance; C_2 = structure with larger mediolateral compliance; YM = young males; OM = older males; T_{II} = duration in Phase 2 (normalized by duration in Phase 1); T_{III} = duration in Phase 3 (normalized by duration in Phase 1); T_{IV} = duration in Phase 4 (normalized by duration in Phase 1); T_{IVa} = duration for reaching control of lateral center-of-mass (COM) movement in Phase 4 normalized by duration in Phase 1 (lateral COM state < threshold of mean ± 2 standard deviations of COM displacement during quiet standing); T_s = duration of completing one step-up movement (from Phase 1 to Phase 4); v_p = lateral COM velocity at trailing-foot push-off (normalized by body height [BH]); v_{zf} = vertical foot placing velocity of trailing foot in Phase 3, normalized by BH (negative sign: downward); R_p = vertical push-off force underneath trailing foot (normalized by body weight); d_{III} = maximum structural lateral displacement in Phase 3 (normalized by BH); d_{IV} = maximum structural lateral displacement in Phase 4 (normalized by BH); e_{IIa} = lateral COM excursion in Phase 2 before reaching the maximum lateral weight transfer rate (normalized by total lateral COM excursion in the stepping movement); # = effects of practice (difference among the 1st to 6th trials); * = effects of compliance; + = effects of age; ! = interaction effects between practice and age; $ = interaction effects between compliance and age; % = interaction effects between practice and compliance. Single symbol, $p < .05$; double symbol, $p < .01$.

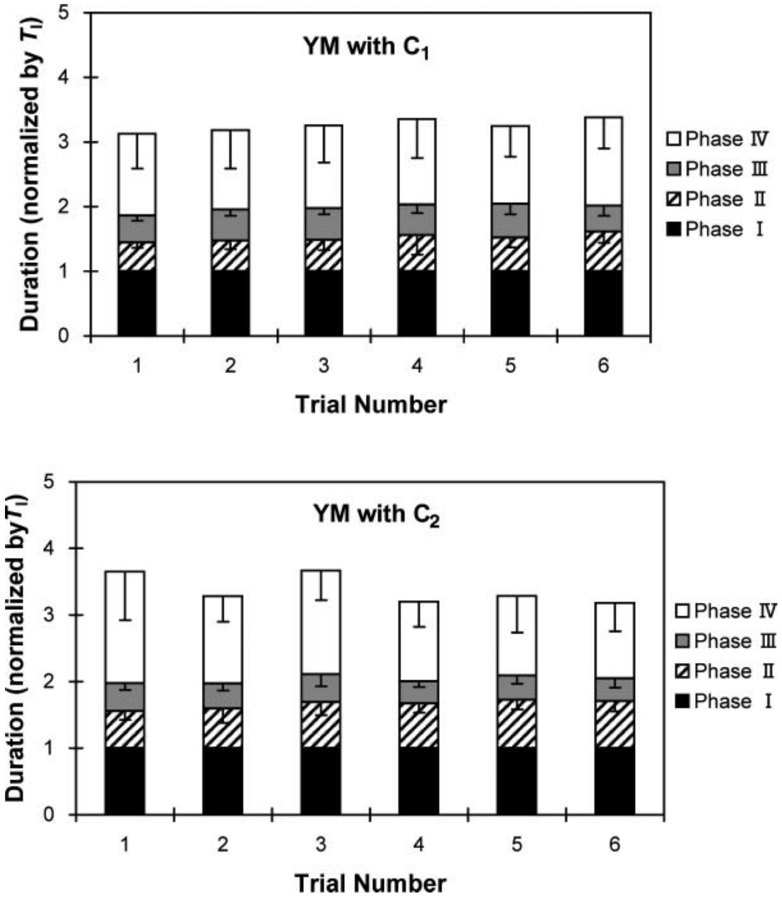

Figure 4. Mean (*SD*) durations in each phase (1 to 4), normalized by T_I, of stepping movements of young males (YM) onto compliant structures (C_1 and C_2).

for reaching control of lateral COM movement in Phase 4 normalized by duration in Phase 1 (lateral COM state < threshold of mean ± 2 standard deviations during quiet standing) as defined in a previous study (Yang & Ashton-Miller, 2006), on the compliant structures: T_{IVa} for OM significantly decreased 45% and 37% in six trials for C_1 and C_2, separately ($p < .001$).

For both groups, the practice effects on structural lateral displacements in Phases 3 and 4 were significant (see Figure 6). As compared with the first trial, the decrease in d_{III} ranged from 14% to 17% for YM and from 26% to 27% for OM in the sixth trial ($p < .001$). Similarly, the decrease in d_{IV} was approximately 8% for YM and ranged from 36% to 40% for OM in the sixth as compared with the first trial ($p < .05/3$), which might result from the significant decrease ($p < .001$) in downward velocity (v_{zf}) that participants used to place the trailing foot on the raised structure. (In the sixth trial, v_{zf} decreased 7% to 15% for YM and from 20% to 23% for OM as compared with the first trial.)

Our previous study showed that in the first stepping trial onto the laterally compliant structures as compared with the rigid structure, participants employed a different movement strategy—moving the COM more laterally toward the lead foot and then developing less lateral COM velocity at the bipedal-to-unipedal transition (Phase 2 to Phase 3) with increasing structural compliance (Yang & Ashton-Miller, 2006). This strategy was not significantly adjusted in repeated trials (see e_{IIa} and v_p in Table 3). At the bipedal-to-unipedal transition (transition from

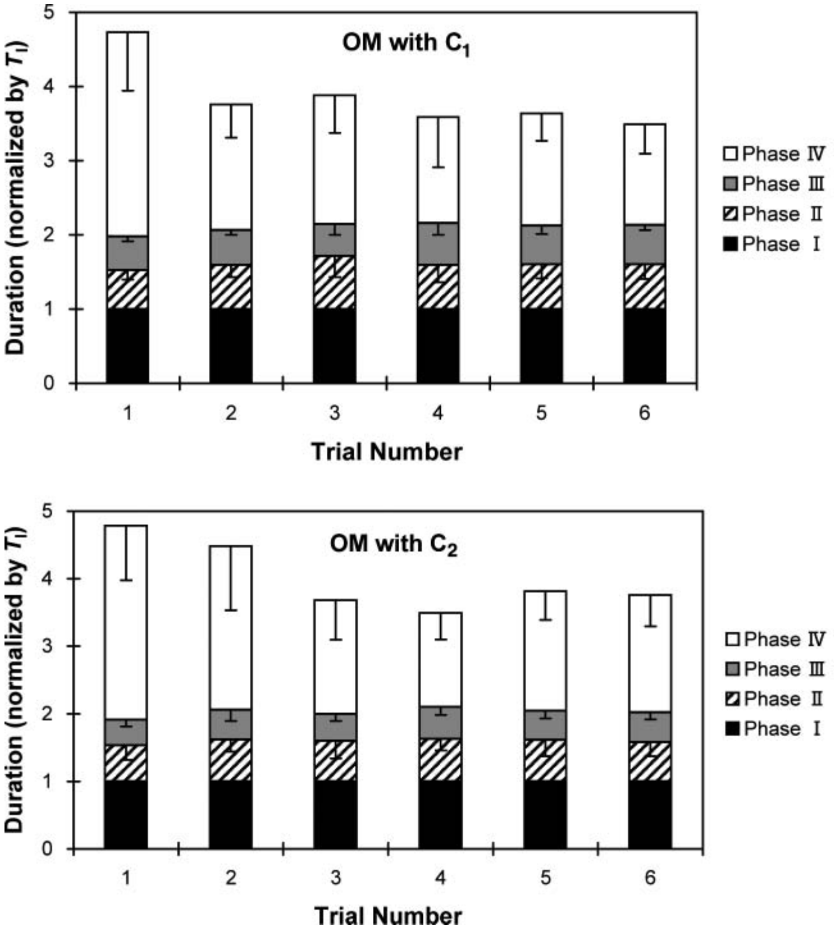

Figure 5. Mean (*SD*) durations in each phase (1 to 4), normalized by T_1, of stepping movements of older males (OM) onto compliant structures (C_1 and C_2).

Phase 2 to Phase 3), the age difference (with no significant effects of practice or structural compliance) in the push-off force (R_p) remained significant in the six repeated trials. OM generally applied a significant, larger push-off force with the trailing foot than did YM to transfer body weight onto the raised structure (see Table 3).

Effects of Structural Compliance After Practice (Comparison of the Sixth Trials)

After five repeated exposures to the same structural compliance, only YM spent significantly more time in Phase 2 ($p < .01$), and both groups of participants spent significantly less time in Phase 3 to step onto C_2 as compared with C_1 (see Tables 3 and 4). Participants needed more time to control lateral COM movement on the raised structure with increasing structural compliance: T_{IVa} was 38% longer for YM and 29% longer for OM for C_2 as compared with C_1 ($p < .05$). In terms of strategy, participants used significantly less lateral COM velocity at the bipedal-to-unipedal transition and used significantly less vertical velocity when placing the trailing foot on the raised structure with increasing structural compliance. There was no significant effect of structural compliance on the other investigated parameters in the sixth trial except for the structural displacements in Phases 3 (d_{III}; $p < .001$) and 4 (d_{IV}; $p < .05$), as shown in Table 4.

The differences in stepping movement between the two age groups decreased across

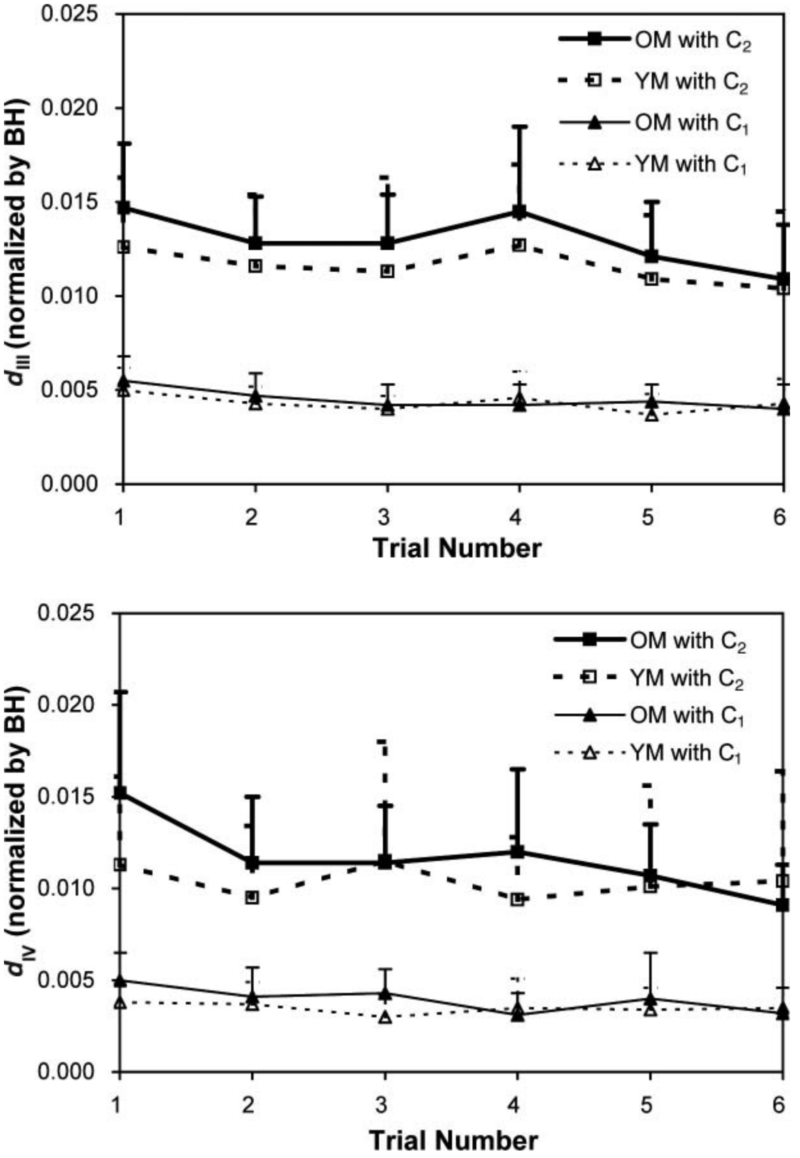

Figure 6. Group mean (*SD*) values of the maximum lateral displacement in Phases 3 (d_{III}) and 4 (d_{IV}), both normalized by body height (BH), during the stepping movement onto the raised compliant structure (C_1 and C_2) in the first to sixth trials (practice effects, $p < .001$ for d_{III}; $p < .05/3$ for d_{IV}). OM = older males; YM = younger males.

six consecutive trials, but the age differences remained significant (see Tables 3 and 4), especially with C_2. In the sixth trial, OM spent 18% more time (compared with 31% more time in the first trial) than did YM to complete the step-up movement for C_2. OM needed 20% to 28% more time than did YM to control lateral COM movement (T_{IVa}) on the compliant structures. Moreover, after practice, OM still needed 53% more time than did YM in Phase 4 (in the first trial, OM needed 71% more time than did YM) to recover their frontal plane balance.

During the stepping movement, particularly for C_2, YM moved their COM farther laterally over the lead foot in the bipedal weight-transfer

TABLE 4: *p* Values of Two Repeated-Measures ANOVAs Examining the Effects of Compliance and Age (a) in the Sixth Trial and (b) Between the First Trial of Young Males (YM) and the Sixth Trial of Older Males (OM)

	In the Sixth Trial		Between the First Trials of YM and Sixth Trials of OM	
Parameter	Compliance	Age	Compliance	Age
T_{II}	.007*	.762	.135	.213
T_{III}	.023*	.044*	.172	.071
T_{IV}	.494	.023*	.011*	.265
T_{IVa}	.034*	.017*	.097	.033*
T_s	.108	.006*	.012*	.059
v_p	.007*	.832	.003*	.390
v_{zf}	.034*	.750	.001*	.485
R_p	.833	.227	.814	.179
d_{III}	<.001*	.256	<.001*	.077
d_{IV}	<.001*	.194	<.001*	.073
e_{IIa}	0.290	.039*	.006*	.030*

Note. T_{II} = duration in Phase 2 (normalized by duration in Phase 1); T_{III} = duration in Phase 3 (normalized by duration in Phase 1); T_{IV} = duration in Phase 4 (normalized by duration in Phase 1); T_{IVa} = duration for reaching control of lateral center-of-mass (COM) movement in Phase 4 normalized by duration in Phase 1 (lateral COM state < threshold of mean ± 2 standard deviations of COM displacement during quiet standing); T_s = duration of completing one step-up movement (from Phase 1 to Phase 4); v_p = lateral COM velocity at trailing-foot push-off (normalized by body height [BH]); v_{zf} = vertical foot placing velocity of trailing foot in Phase 3, normalized by BH (negative sign: downward); R_p = vertical push-off force underneath trailing foot (normalized by body weight); d_{III} = maximum structural lateral displacement in Phase 3 (normalized by BH); d_{IV} = maximum structural lateral displacement in Phase 4 (normalized by BH); e_{IIa} = lateral COM excursion in Phase 2 before reaching the maximum lateral weight transfer rate (normalized by total lateral COM excursion in the stepping movement).
*$p < .05$.

phase as compared with OM: e_{IIa} value was 34% greater for YM compared with OM for C_2.

Comparison Between the First Trial of YM and the Sixth Trial of OM

When comparing the stepping movements of OM in the sixth trial (after practice) with YM in the first trial, group differences were not significant for most parameters, except for e_{IIa} (p = .030) and T_{IVa} (p = .033) (see Table 4). After practice, OM, as compared with YM in the first trial, still needed significantly more time (24% more for C_1; 16% more for C_2) to control lateral COM movement in Phase 4, although T_{IVa} for OM decreased significantly with practice.

DISCUSSION

The results led us to reject the primary null hypotheses that there are no significant (a) movement adjustments, (b) age differences in those adjustments, or (c) effects of structural compliance on the movement adjustments in the repeated exposures to mounting a raised structure with a given lateral compliance.

As reported by Yang and Ashton-Miller (2006), the participants' movements were significantly affected by the "unexpected" structural compliance during the first trial of the forward-and-up stepping movements. Healthy adults needed more time to recover balance in the ML direction and to complete the stepping movement as structural compliance was increased. As expected, the stepping movements onto the rigid structure (C_0) was not significantly affected by practice in either group. This is not surprising, given the overlearned nature of the step-up movement, that is, the need to frequently negotiate fixed steps and stairs in daily life. When stepping onto the laterally compliant structures, however, these healthy males were able to adjust their stepping strategy and significantly reduce the time needed to complete one step-up movement in the repeated trials onto the same structure. Although YM showed significant adjustments only for C_2, OM were able to adjust their stepping movements to adapt to the lateral compliance, and they reduced the stepping duration within six consecutive trials (mainly in the first three trials), for both C_1 and C_2.

After practice, both groups of participants significantly lengthened the bipedal support phase (Phase 2). With significant age differences ($p < .01$), OM spent a similar amount of time in this phase for C_1 and C_2, whereas YM spent significantly more time as structural compliance increased. This strategy difference indicates that YM, but not OM, tend to use the bipedal support phase to prepare for anterior and lateral weight transfer onto a raised structure with increasing compliance. The significant effect of age on e_{IIa} (YM moved COM more laterally than did OM before transferring most of body weight for C_1 or C_2) in both the first and sixth trials (see Table 3) also explains the difference in this weight-transfer strategy.

No significant practice effect was found in the duration of the unipedal support phase (Phase 3). In fact, the large within- and between-subjects variations of T_{III} illustrate the difficulty of adjusting unipedal movements, especially for elderly men, on a laterally compliant structure. In the human frontal plane, ankle inversion-eversion torque is one of the primary means to control postural balance (Rietdyk, Patla, Winter, Ishac, & Little, 1999). Physiological limits of this control mechanism (Ottaviani, Ashton-Miller, & Wojtys, 2001) might constrain the feasible adjustments to be made to the movement in this phase, especially with a laterally compliant structure. However, these healthy participants showed their ability to stabilize the human-compliant structure system by reducing the lateral displacement of the structure.

The balance recovery phase (Phase 4) seems to be the most critical, yet most adjustable, phase in repeated step-up movements. This finding corroborates behavior found in the first trial (Yang & Ashton-Miller, 2006). The majority of the reduction in *T*s from the first to sixth trials occurred in this phase. The interaction effects between age and practice indicate that OM shortened the duration in this phase significantly more than did YM, although YM, compared with OM, with or without practice, usually needed less time to recover their balance in the plane of most compliance (frontal plane).

The significant adjustments described primarily occurred within the first two or three trials (see Figures 3 through 6), which demonstrates that the participants could reach an "optimal" movement strategy after the first three consecutive trials. There are also interaction effects between practice and age: The between-trial adjustments of YM were much smaller than those of OM. As described in the previous study (Yang & Ashton-Miller, 2006), C_1 and C_2 had similar effects on stepping duration in the first trials for OM, whereas for YM, C_1 affected the stepping strategy but not the total duration. Thus, YM (but not OM) might be able to identify the value of the smaller structural compliance and adopt a proper stepping strategy in the first stepping trial. Moreover, YM could reach the "optimal" status or strategy at an earlier stage than could OM when stepping onto a raised structure with unfamiliar structural compliance.

These age differences in structural compliance identification and stepping strategy adjustments could be reasons elderly people fall more frequently than young adults from raised structures (Faergemann & Larsen, 2000, 2001) and could explain why elderly people do not feel confident standing on chairs or similar raised structures (Powell & Myers, 1995). From our results, we predict that older adults might be more prone to lose their balance on the first attempt to balance on a raised structure than on subsequent attempts.

Although YM did not reduce *T*s as much as did OM in the repeated trials, both groups of participants could significantly reduce the maximum displacement of the compliant structure, which was induced by the forward-and-up stepping movement. Through practice, healthy male adults are able to adjust strategies, which include significantly decreased downward velocity of the trailing foot (v_{zf}), to reduce lateral oscillations of the structure and stabilize the human-compliant structure system during the stepping movement.

The previously described results were based on 10 participants in each age group who were barefoot. Although the sample size was limited and the test results might be different from movement behavior with various footwear, our goal was to determine primary age differences and practice effects on step-up movements onto laterally compliant raised structures, such as stepladders or stools, that are used at home frequently. In addition, in our study, we asked the participants to fold their arms in front of the chest while performing the step-up movements. Although this experimental design might have limited the means that the participants could use to maintain an upright posture, our purpose was to simplify the movement patterns and ensure accurate estimation of whole-body COM from the motion capture data, hence to obtain the insight of the primary control mechanism of stepping movements onto laterally compliant raised structures.

Comparison in the Sixth Trial (After Practice)

The significant age differences that existed in the sixth trial of stepping movements led us to reject one of the secondary null hypotheses, namely, that after practice, there is no age difference in the stepping movements. Age differences remained statistically significant after five repeated trials. This finding provides more evidence that age effects exist in the control mechanism of this stepping movement. This control mechanism might consist of a “feedforward” strategy planner and a feedback controller for integrating sensory information into movement commands.

As the subjects had no prior knowledge to the structural compliance, the age differences in the first stepping trial might be caused by defects or noise in the sensory system or by improper values of the feedback gain. The effect of age after five practice trials further confirms the possibility that there are age differences in this control mechanism. The extended balance recovery time for older participants could also result from age-related sensory and/or motor delays (Earles & Salthouse, 1995; Larsson & Ansved, 1995; Lin & Woollacott, 2002; Porciatti, Fiorentini, Morrone, & Burr, 1999; Woollacott, 1993).

As compared with YM, older participants moved their COM less far laterally in the bipedal weight-transfer phase (Phase 2); that is, OM maintained a larger lateral distance between COM and the lead foot in this phase. This strategy might help elderly people generate a larger push-off force on the trailing foot to compensate for the lack of knee extension strength (Melzer, Benjuya, & Kaplanski, 2000) at the step-up phase (transition between Phases 2 and 3).

The effect of structural compliance on stepping duration (Ts) was eliminated by both groups after practice. Therefore, we did not reject one of the secondary null hypotheses, that there is no effect of structural compliance on stepping movements after practice. In terms of strategy, participants significantly adjusted movement in Phases 2 and 3 and in the controlling lateral COM movement subphase (see T_{IVa} in Tables 3 and 4) to accomplish the stepping movement onto the raised structure with different values of compliance.

Can the Elderly Compensate for the Age Differences by Practice?

After practice in several trials, OM were able to adjust their stepping movement to reach a movement strategy that was similar to the strategy that YM used in the first trial (see Tables 3 and 4). In the sixth repeated trial, OM needed only slightly more (without statistical significance) time than did YM in the first trial to complete the stepping movement onto the laterally compliant raised structures. This finding suggests that OM are capable, but need practice, to identify and adapt to the lateral structural compliance during the stepping movement onto a raised structure.

After a small number of practice trials, healthy adults are able to adjust their stepping movements to adapt to the structural compliance in the ML direction. The unfamiliarity of the environmental property (such as structural compliance) might affect the control of human balance and could cause accidents, such as falls from stepladders. However, healthy adults can reduce the effect of structural compliance on balance with practice. Users, especially elderly ones, should be advised to use caution and practice when stepping onto, or balancing on, a compliant raised structure.

ACKNOWLEDGMENTS

This study was supported by U.S. National Institute of Health Grant Nos. P01 10542 and P50 08808 and by Republic of China (Taiwan) National Science Council Grant NSC-98-2218-E-009-007.

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Date received: November 5, 2009
Date accepted: March 2, 2010