年齡與結構側向撓度對登上高於地面結構動作之影響
Effects of Age and Structural Lateral Compliance on Forward-and-up Stepping Movements

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摘要

本研究以實驗量測與生物力學分析量化練習與受測者年紀對向前登上一高於地面結構（例如梯子）動作的差異，經由練習，受測者有能力調整他們的動作去適應結構的側向撓度。因此建議使用者（特別是年長者）在使用離地面有一高度且有側向撓度之結構時（例如梯子），能特別小心並在需於其上工作前重複練習幾次登上動作。

關鍵詞：跌倒，安全，梯子，平衡

Abstract

We investigated the effects of practice and advancing age on the kinematic and kinetic behavior of 20 healthy male adults (10 young males (YM) aged less than 30 years and 10 older males (OM) aged over 65 years) stepping up onto rigid (C_0), smaller-compliant (C_1), and larger-compliant (C_2) raised structures. After a small number of practice trials, these healthy male adults are able to adjust their stepping movements to adapt to the lateral structural compliance. Users, especially the elderly, should be advised to use caution, and better practice, when stepping onto, or balancing on, a compliant raised structure.

Keywords: falls, safety, stepladder, balance

I. INTRODUCTION

Falls from laterally-compliant structures, such as stepladders, cause injuries at workplace and at home across the age spectrum; however, fall-related injuries become more frequent and more serious in older populations [1, 2]. Most stepladders, especially old ones, are not rigid but have structural compliance in the lateral direction (corresponding to the frontal plane of the human user). Structural compliance in this direction might place greater demands on users' balance capabilities of stabilizing the mechanical system composed of the human and the compliant structure on which they stand. Healthy adults, especially the elderly, have been shown to take significantly more time to complete a single step-up movement onto a raised structure with unexpected structural compliance [3]. While these findings are important, it is also relevant to know whether any adaptive changes occur during repeated exposures to the same structural compliance. In addition, it is not known whether any age effects exist in 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 [4, 5]. However, adaptation of movements in response to the self-induced perturbations, while stepping onto a laterally-compliant structure, has not yet been studied. The purpose of this study, therefore, was to investigate whether subjects demonstrate practice or learning effects in this behavior. We tested the primary null hypotheses that there are (a) no significant practice effects in stepping up onto a laterally-compliant structure in repeated trials, (b) no age effects on this behavior between healthy young and older men, and (c) no effects of structural compliance on these movement adjustments. The secondary null hypotheses are that after practice, there is (a) no age difference in the stepping movements, and (b) no effect of structural compliance on stepping movements.

II. METHODS

The data of male subjects of the previous study [3] were further analyzed here. Detailed subjects information and experimental protocols are described below.

Twenty healthy male subjects, 10 young males (YM) aged 26±3 years and 10 older males aged 72±3 years (no

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differences in body height and weight between YM and OM), were asked to stand bare-footed on firm ground, and then step forward and up onto a 0.178 m (7 inch)-high structure at a self-selected comfortable speed. The lateral compliance of the structure could be covertly adjusted to one of three different values (measured at the structural top surface): rigid ($C_0 < 10^{-5}$ m/N), smaller compliance ($C_1 = 1\times10^{-4}$ m/N), and larger compliance ($C_2 = 2\times10^{-4}$ m/N). Six stepping trials were performed with each compliance. Trial order was C_0, C_1, and C_2, interspersed by different numbers of blocks of six C_0 trials to prevent subjects knowing when a compliance change occurred. Adaptive changes in the stepping movements were examined by comparing data from the first to sixth trials in each compliance condition.

The primary parameters investigated were (1) the total time each subject used to complete the step-up movement normalized by the time used from initiating weight transfer till the lead foot contacting the raised structure normalized by the time used in the first phase (Ts), and (2) the maximum lateral displacement of the compliant structure, normalized by the subject's body height induced by the forward-and-up stepping movement (d_M). The secondary parameters were (3) the time used in the weight-transfer preparation phase (T_{II}) – time between the first contact of the lead foot with the raised structure and the push-off state of the trail foot from the ground, and (4) the time used in the balance recovery phase (T_{IV}) – duration from the first contact of the trail foot with the raised structure till the recovery of state of quiet standing on the raised structure, both normalized by the time used in the first phase. Repeated measure analyses of variance (rm-ANOVA) were performed to examine the effects of practice, structural compliance, and age on the investigated parameters. A post-hoc rm-ANOVA was used to examine the effects of structural compliance and age on stepping movements after practice (in the sixth trial). Additional post-hoc rm-ANOVA was performed to compare movement parameters of the first trial of YM with those of the sixth trial of OM. *P*<0.05 was considered statistically significant unless otherwise noted.

III. RESULTS

1. Effects of Practice

Practice significantly ($p<0.001$) affected the stepping duration (Ts) onto the compliant structures (C_1 or C_2) of healthy male adults, especially for older males. Figure 1 shows the changes of Ts in each subject group under three test conditions. For both groups, Ts on the rigid structure (C_0) was not significantly affected by practice. When stepping onto the compliant structures, Ts for older males decreased significantly with practice, while Ts for young males decreased slightly with C_2 from the first to sixth trials but remained similar with C_1 within six consecutive trials. Since most movement adaptation (as shown in Figure 1) occurred on the compliant structures (C_1 or C_2), only presents data at the beginning and after practice of the stepping movements onto those two compliant structures. The effects of age ($p<0.01$) and interaction effects between practice and age ($p<0.01$) were both significant. Within two (for C_1) or three (for C_2) trials, older males significantly reduced the total duration needed for the stepping movements onto the laterally-compliant structures. Ts for OM decreased 21% from the first to second trials with C_1 and 23% from the first to third trials with C_2, while YM showed a relatively smaller decrease (15%) in Ts from the first to sixth trials with C_2, but no large changes with C_1.

In the weight-transfer preparation phase in the sixth compared to the first trial, YM used 36% and 25% more time with C_1 and C_2, respectively, while OM used 13% and 7% more time with C_1 and C_2, respectively (see T_{II} in Table 1, $p<0.05$). It also appears that after practice (in the sixth trial) YM relied more than OM on this phase while transferring body weight onto the large-compliant structure (C_2). In the balance recovery phase in the sixth compared to the first trial, OM spent 51% and 40% less time with C_1 and C_2, respectively, while YM spent 32% less time with C_2, but 8% more time with C_1 (T_{IV} in Table 1, $p<0.001$).

For both groups, practice significantly ($p<0.001$) reduced the maximum structural lateral displacement (Figure 2). As compared to the first trial, the decrease in d_M ranged from 14 to 17% for YM and from 26 to 27% for OM in the sixth trial.

2. Effects of Structural Compliance after Practice (Comparison in the Sixth Trials)

After five repeated exposures to the same structural compliance, YM used significantly more time (OM used similar amount of time) in the weight-transfer preparation phase ($p<0.01$; see Table 1). The differences in stepping movement between the two age groups decreased over six consecutive trials, but the age differences remained significant ($p<0.05$, see Table 1), especially with the larger-compliant structure (C_2). In the sixth trial, OM used 18%

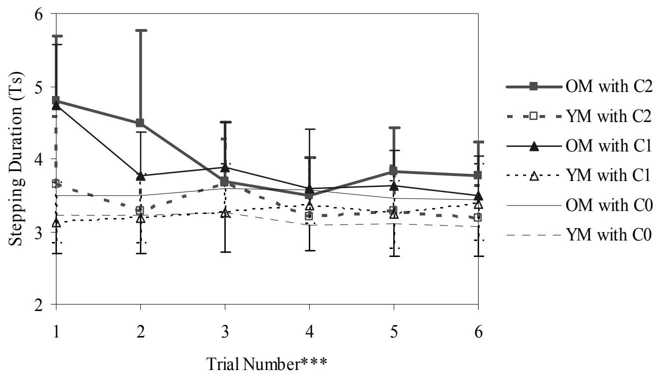

Fig. 1 Mean values (error bars: standard deviations) of total duration (Ts, normalized by the time used in the first phase T_I, time used in the preparation phase) of one stepping movement onto the raised structure with three values of structural compliance in six consecutive trials each (***: $p<0.001$). Age effects: $p<0.01$; interaction effects between age and practice: $p<0.01$.

Table 1 Mean (SD) parameter values in the 1st and 6th trials in each subject group on the compliant structures.

Condition	YM with C_1		OM with C_1		YM with C_2		OM with C_2	
Parameter	1st trial	6th trial	1st trial	6th trial	1st trial	6th trial	1st trial	6th trial
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_{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)
Ts ###, **, ++, !!	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)
d_M ###, ***, %	0.005 (.001)	0.004 (.001)	0.006 (.001)	0.004 (.001)	0.013 (.004)	0.010 (.004)	0.015 (.003)	0.011 (.003)

Effects of practice (difference among the 1st to 6th trials): #: p<0.05; ###: p<0.001. Effects of compliance: **: p<0.01; ***: p<0.001.
Effects of age: +: p<0.05; ++: p<0.01. Interaction effects between practice and age: !!: p<0.01; !!!: p<0.001.
Interaction effects between compliance and age: $$: p<0.01. Interaction effects between practice and compliance: %: p<0.05.

more time (compared to 31% more time in the first trial) than did YM to complete one step-up movement onto C_2. After practice, OM still needed 53% more time than did YM (in the first trial, T_{IV} for OM was 71% larger than that for YM) to recover the frontal-plane balance.

3. 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 all investigated parameters (Table 1). Older males spent slightly more time (12% more with C_1 and 3% more with C_2), but without statistical significance, in the sixth trial, compared to YM in the first trial, to complete one step-up movement onto the laterally-compliant structures. After practice, older males, as compared to YM in the first trial, still needed significantly more time (24% more with C_1 and 16% more with C_2) to control lateral center of mass movement in the balance recovery phase (see T_{IV} in Table 1).

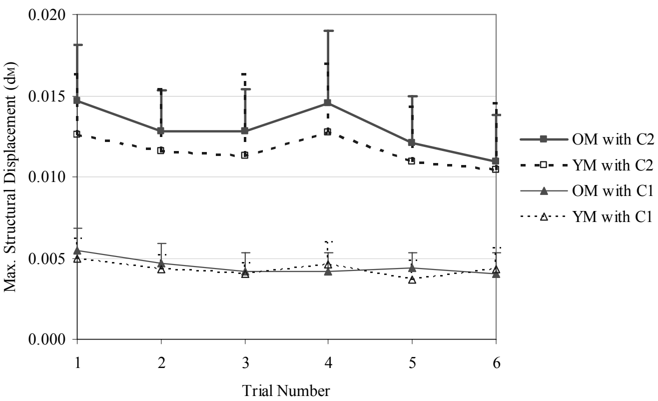

Fig. 2 Group mean (SD) values of the maximum lateral displacement, normalized by each subject's body height, during stepping movement onto compliant structures (d_M) (practice effects: p<0.001).

IV. DISCUSSION

The results led to the rejection of all the primary null hypotheses that there are no significant (a) practice effects in stepping up onto a laterally-compliant structure in repeated trials, (b) age effects on this behavior between healthy young and older men, and (c) effects of structural compliance on these movement adjustments. As reported in the previous study [3], the subjects' 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 mediolateral direction and complete the stepping movement with increasing structural compliance. As expected (since the rigid structure was designed to be a baseline comparison), the stepping movements onto the rigid raised structure (C_0), which also represents an activity of daily living such as climbing stairs or fixed ladders, was not significantly affected by practice for either subject group. When stepping onto the laterally-compliant structures, however, these healthy male adults were able to adjust their stepping strategy and significantly reduced the time needed to complete one step-up movement in the repeated trials onto the same structures. Although young males only showed significant adjustments with the larger-compliant structure (C_2), but not with C_1, older males were able to adjust their stepping movements to adapt to the lateral compliance and reduced the stepping duration within six consecutive trials (mainly in the first three trials) onto both laterally-compliant structures.

After practice, both groups of subjects significantly lengthened the weight-transfer preparation phase. With significant age differences (p<0.01), OM spent a similar amount of time in this phase with C_1 and C_2, while YM used significantly longer time with increasing structural compliance. This strategy difference indicates that young males, but not the elderly, tend to utilize this bi-pedal-support phase to prepare for anterior and lateral weight transfer onto a raised structure with increasing structural compliance.

Similar to the movement in the first trial presented in our previous study [3], the balance recovery phase seems to be the most critical but most adjustable phase in the repeated stepping movements. The majority of the duration reduction 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, though YM compared to OM, with or without practice, usually needed less time to recover standing balance in the mediolateral direction on the laterally-compliant structures.

The significant adjustments described above primarily occurred within the first two or three trials (see Figure 1), which demonstrates that the subjects 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 are much smaller than those of OM. As described in the previous study [3], C_1 and C_2 had similar effects on stepping duration in the first trials for older males, while for YM the smaller compliance (C_1) affected the stepping strategy but not the total duration. Thus, young males (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, healthy young males could reach the "optimal" status or strategy at an earlier stage than could healthy older males when stepping onto a raised structure with unfamiliar structural compliance. These age differences in structural compliance identification and stepping strategy adaptation could be reasons why the elderly fall more frequently than young adults from raised structures [2, 6], and also explain why the elderly do not feel confident standing on chairs or similar raised structures [7]. From our results we would predict 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 Ts as much as did OM in the repeated stepping trials, both groups of subjects 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 in order to reduce lateral oscillations of the structure and stabilize the human-compliant structure system during the stepping movement.

1. Comparison in the Sixth Trial (After Practice)

The significant age differences which existed in the sixth trial of stepping movements led us to reject one of the secondary null hypotheses, namely that after practice (five repeated exposures) there is no age difference in the stepping movements. Age differences remained statistically significant after five repeated trials. This 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. With no prior knowledge, the age differences in the first stepping trial might be caused by the defects or noise in the sensory system, or improper values of the feedback gain. The effect of age after five practice trials further confirms the possibilities of age differences existing in this control mechanism. The extended balance recovery time for older subjects could also result from age-related sensory and/or motor delays [8-13]. We used a control model to evaluate the effects of these system variables on this movement control in a separate study [14].

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.

2. Can the Elderly Compensate for the Age Differences by Practice?

After practice in several trials, healthy older males were able to adjust their stepping movement to reach an "optimal" strategy, which was also similar to the strategy that healthy young adults used in the first stepping trial (Table 1). In the sixth repeated trial, older males only needed slightly more (with no statistical significance) time than did YM in the first trial to complete the stepping movement onto the laterally-compliant raised structures. This suggests that older male adults are capable, but need practice, to identify and adapt to the lateral structural compliance during the stepping movement onto a raised structure.

V. CONCLUSIONS

After a small number of practice trials, healthy adults (both young and older) are able to adjust their stepping movements to adapt to the structural compliance in the mediolateral 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 the elderly, should be advised to use caution and better practice when stepping onto, or balancing on, a compliant raised structure.

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