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# Stepping Responses during Forward and Backward Fall Recovery between Thai Elderly Fallers and Non-fallers

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**Abstract.** [Purpose] The present study compared the ground reaction forces and temporospatial characteristics of the initial foot movement following anteroposterior platform perturbation between elderly fallers and non-fallers. [Subjects] Eighty-one elderly female subjects aged between 60 to 70 years were divided into faller (N=36) and non-faller (N=45) groups. [Methods] A motorized platform translation was applied as a perturbation. The response characteristics were recorded using a forceplate and a six-video camera 3D Vicon™ motion analysis system. [Results] Both faller and non-faller groups showed a forward single step pattern greater than a backward single step pattern. The swing duration time of the non-faller group was significantly longer than that of the fallers, whereas step velocity of the fallers showed higher values than that of the non-fallers during forward single step. [Conclusion] The step ability in the faller group was decreased compared to the non-faller group during the forward single step. The findings suggest that the muscle performance of the primary muscles for balance recovery should be promoted in the elderly. Moreover, stability and ability to stand on one leg should be a measurement and training concern for the elderly to reduce the likelihood of falls.
**Key words:** Elderly, Fall, Stepping response

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## INTRODUCTION

Falls are a major health problem for the elderly[1)]. The main causes of falls are slipping (52.8%) and tripping (26.4%)[2)]. Deterioration of postural control ability is an important factor of falls in the elderly[3)]. Stability can be challenged by perturbation of the center of mass (COM) (e.g., impact with an object during volitional movement) or by perturbation of the base of support (BOS) (e.g., slipping, tripping, acceleration of the support surface during vehicular motion).

Disturbances of stance can evoke a variety of postural and balance-related responses[4)]. Stepping is a commonly executed protective response for balance recovery in the natural environment[5)]. It can serve to alter the base of support in order to preserve stability in defense against perturbation. Humans often avoid falling in the event of a perturbation to standing balance by taking one or more steps[5)]. Stepping responses can be induced by causing displacement of either the COM (e.g. waist-pull) or the BOS (e.g. support surface translation).

Previous studies of compensatory stepping during forward and backward fall recovery have reported age-related differences in the use of a step to recover balance[6–8)]. The steps taken by the old compared with those of the young have slower execution time[6)], earlier liftoff and landing time, shorter step duration[8,9)], shorter step length[7)], less height[9)], and slower velocity[8)].

It has been reported that elderly fallers demonstrate shorter latency of the lateral gastrocnemius response[10)], slower reaction times[11)], decline in lower limb proprioception, decrease in quadriceps and ankle dorsiflexor muscles strength[12)], and reduction of hip flexor and ankle dorsiflexor muscles flexibility[13)]. Therefore, stepping responses between elderly fallers and non-fallers are probably different.

The protective stepping in forward and backward balance recovery related to history of falls has been studied[14–16)]. Elderly fallers are more likely to step than the non-fallers during the forward step[14)]. Furthermore, fallers had an earlier liftoff time and longer step duration[15)]. Fallers usually take multiple small steps during backward destabilization[16)]. It has been reported that compared to the young or elderly non-fallers[5)], elderly fallers[15)] had greater sideways body motion toward the stepping side at step contact and more laterally directed foot placement in response to forward fall recovery.

However, most studies have compared stepping responses between elderly fallers and non-fallers using the method of waist-pull perturbation which initiates perturbation at the torso or COM[14–16]. It was found that differences in the method of perturbation affect the stepping response[17]. A support surface translation can simulate an event of slip or trip which are the most frequently reported causes of falls among older adults[2]. Thus, stepping responses induced by support surface translation between elderly fallers and non-fallers are interesting to study.

The ground reaction force (GRF) of the stepping foot is a primary contributor to retarding forward rotation of the body during a stumble[18]. Excessive demand of the shear force on the contact foot could increase the risk of slipping. The contact force of the stepping leg occurring during landing is the other factor that could influence the regulation of compensatory stepping reactions[19]. During recovery of balance after a trip, older fallers showed less ability to rapidly generate forces in the lower limbs and insufficient reduction of the angular momentum in all support limb joints[20]. It was found that elderly fallers have greater difficulty recovering balance with a single step during forward[14] and backward[16] disturbances. For fallers, the mechanism of balance recovery and the GRFs during step landing period responding to standing balance perturbation might be problematic.

To clarify the stepping responses during forward and backward fall recovery between elderly fallers and non-fallers, the GRFs and temporospatial characteristics of the initial foot movement were investigated to learn more about the cause of falls. We hypothesized that there was difference between fallers and non-fallers in the GRFs and temporospatial characteristics of the initial foot movement during forward and backward fall recovery.

## SUBJECTS AND METHODS

*Subjects*

Elderly female subjects aged 60–70 years participated in the study. All subjects were active and could walk without assistive devices. Subjects were excluded if they were unable to understand and follow verbal instructions and had a Thai Mental State Examination score of less than 23[21]. They were also excluded if they had neurological or sensory disorders, abnormal motor function or manifest muscular weakness, a history of back or lower extremity surgery, joint arthritis affecting standing or walking, musculoskeletal problems affecting posture or taking medication which would affect postural balance. Prior to participation in the study, each subject signed an informed consent form to comply with ethics guidelines dictated by the Ethical Committee on Research involving Human Subject, Faculty of Medicine Siriraj Hospital, Mahidol University, Thailand.

In the present study, fallers were those who reported unintentionally and unexpected coming to rest on the floor at a level lower than the knees during routine activities during the 6 months prior to participation in the study. Falls caused by fainting, illness, syncope, or during unusual activities in which an active healthy person may fall were discounted.

*Methods*

Subjects wore a safety harness which did not restrict movement and looked straight ahead with eyes open, and arms beside the body in quiet barefoot standing with a stance width of 11% of standing body height[22]. Their standing posture was disturbed by translation of the motorized platform on which they stood with a peak speed of 0.85 m/s and peak acceleration of 1.4 m/s$^2$ for approximately 1 second. The forceplate was placed to the front or back of the subject, when a forward or backward step was evoked. Each subject randomly performed 1 trial per direction. To suppress the effect of eye movement on balance performance, subject was instructed to look straight ahead in front of them at eye level. In addition, subjects were instructed to “try to keep from falling”. Subjects were given no specific instructions regarding any other aspect of their behavior, i.e., arm and foot motions were unconstrained. In order to distract subject’s attention from the upcoming platform motion, subjects were given a random number between 50 and 100, and asked to repeatedly subtract 3 from the chosen number as quickly and accurately as possible until the onset of the motion.

The response characteristics were recorded using the forceplate and 3D Vicon™ motion analysis system. The forceplate was mounted at the center of a platform (1 m × 1.5 m). Six video cameras were used to record subjects stepping onto the forceplate at a sampling frequency of 200 Hz. Force data were collected at a 1,000 Hz sampling rate and synchronized with the video images using the Workstation™ program. Data were digitally low-pass filtered with a 4th order Butterworth filter (10 Hz for trajectories and 15 Hz for force data) before analysis. A digital video camera was also used to record the foot movement.

The parameters consisted of the step pattern, GRFs, step liftoff time (seconds), step landing time (seconds), swing duration time (seconds), step length (m), step height (m), and step velocity (m/s). The forceplate signals were used to determine the step timing relative to the onset of platform translation. Step liftoff time was the time of the initial foot-off from the platform. Step landing time was the time when the foot landed on the forceplate or the instant when the vertical GRF rose above 10 N. Swing duration time was the interval between step liftoff to step landing times. The landing period was the time from step contact to the end of landing and the end of landing was defined as the time when the knee of the stepping leg reached maximum flexion during stepping. The position of the 2nd metatarsal marker was used to calculate the step length and step height. Step velocity was the step length divided by the swing duration time.

The GRF during the stepping response was measured in three directions, the x, y, and z axes. Peak vertical GRF (z axis) was recorded during forward and backward steps. The anterior-posterior (AP) and medial-lateral (ML) direction (x, y axes) forces were recorded at the same time as peak vertical GRF.

For statistical analysis, the data of stepping were compared between the faller and non-faller groups using the independent t-test for normally distributed data or the Mann-Whitney U test for other distributions. Differences were considered statistically significant at $p<0.05$.

## RESULTS

Eighty-one elderly female subjects aged between 60–70 years were divided into 2 groups, faller (n = 36) and non-faller (n = 45) groups. Most subjects were housewives; 19 out of the 36 fallers (52.8%) and 24 out of 45 the non-fallers (53.3%). Location of participants dwellings, educational level, medical history, and exercise behavior are shown in Table 1. History and causes of falls in the faller group are shown in Table 2. The step responses to each perturbation when a subject landed clearly on the forceplate are presented in Figure 1.

The peak vertical GRF is presented as absolute values in Table 3. The comparison showed no significant differences of peak vertical GRF between the faller and non-faller groups in forward and backward steps. The ML GRF is presented as absolute values in Table 4. Although, there were no significant differences in ML GRF between the faller and non-faller groups, non-fallers demonstrated a higher ML GRF than fallers during the forward single step, while fallers showed higher ML GRF than non-fallers during forward and backward multiple steps. The AP GRF of each group during forward and backward steps is shown in Table 5. A negative value represents the posterior

**Table 1.** Characteristics of subjects (n = 81)

| Characteristics | Fallers (n) | Non-fallers (n) |
|---|---|---|
| Dwelling place of participants | | |
| City | 24 | 27 |
| Suburban | 12 | 18 |
| Medical history | | |
| No medical history (healthy) | 13 | 19 |
| Diabetes mellitus | 6 | 10 |
| Hypertension | 15 | 15 |
| Hypercholesteremia | 5 | 7 |
| Other | 3 | 4 |
| Exercise behavior | | |
| Tai chi | 5 | 7 |
| Aerobic exercise | 4 | 4 |
| General exercise | 4 | 9 |
| Yoga | 2 | 1 |
| Walking 15–30 minutes | 7 | 3 |

**Table 2.** The history and causes of falls in faller group (self report)

| Characteristics | Number of subjects |
|---|---|
| History of fall | |
| 1 time | 24 |
| ≥ 2 times | 12 |
| Causes of fall | |
| Stumble, Trip | 15 |
| Slide, Slip | 22 |
| Other causes e.g. descending stairs, rise from chair | 4 |

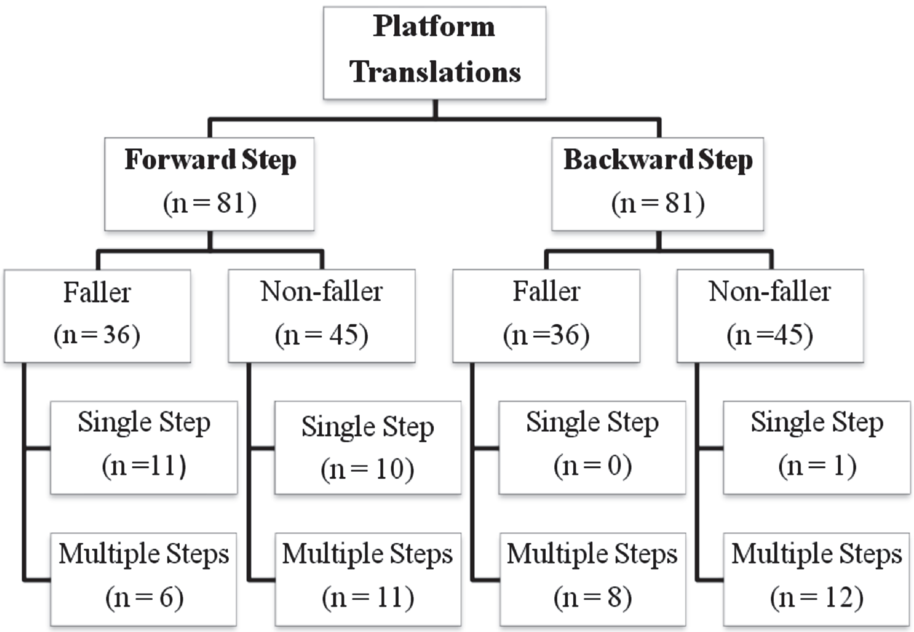


**Fig. 1.** Schematic diagram of step responses on the forceplate. Only the results when the foot landed clearly on the forceplate are shown.

**Table 3.** The peak vertical GRF of the faller and non-faller groups

| Patterns | Peak vertical GRF (times body weight) | |
|---|---|---|
| | Faller (Mean ± SD) | Non-faller (Mean ± SD) |
| Forward Single Step | 1.69 ± 0.29 (n = 11) | 1.61 ± 0.34 (n = 10) |
| Forward Multiple Steps | 1.74 ± 0.29 (n = 6) | 1.72 ± 0.47 (n = 11) |
| Backward Multiple Steps | 1.43 ± 0.28 (n = 8) | 1.47 ± 0.20 (n = 11) |

**Table 4.** The medial-lateral GRF of the faller and non-faller groups

| Patterns | ML GRF (times body weight) | |
|---|---|---|
| | Faller | Non-faller |
| | (Mean ± SD) | (Mean ± SD) |
| Forward Single Step | 0.07 ± 0.07 (n = 11) | 0.09 ± 0.06 (n = 10) |
| Forward Multiple Steps | 0.10 ± 0.07 (n = 6) | 0.09 ± 0.06 (n = 11) |
| Backward Multiple Steps | 0.08 ± 0.03 (n = 8) | 0.06 ± 0.03 (n = 11) |

Note: The ML GRF is shown as absolute values.

direction and a positive value represents the anterior direction during forward step. A negative value represents the anterior direction and a positive value represents the posterior direction during backward step. Most subjects in the faller and non-faller groups demonstrated the posterior direction of AP GRF during forward single and multiple steps: 82% or 9 out of 11 subjects in the faller group and 100% or 10 out of 10 subjects in the non-faller group during forward single step; and 66% or 4 out of 6 subjects in the faller group and 64% or 7 out of 11 subjects in the non-faller group during forward multiple steps. More non-fallers, 58% or 7 out of 12 subjects, demonstrated the anterior direction of AP GRF, whereas more fallers, 71% or 5 out of 7 subjects, demonstrated the posterior direction of AP GRF during backward multiple steps.

The temporospatial characteristics of stepping response were compared for 6 parameters: step liftoff time (sec.), swing duration time (sec.), step landing time (sec.), step length (m), step height (m), and step velocity (m/s) as shown in Table 6. There were significant differences in the swing duration time ($p = 0.048$) and step velocity ($p = 0.019$) between the faller and non-faller groups during forward single step. The swing duration time of fallers was significantly shorter than that of non-fallers, whereas the step velocity of fallers was higher than that of the non-faller. No significant differences in any parameters of the temporospatial characteristics between the faller and non-faller groups were observed during forward and backward

**Table 5.** The anterior-posterior GRF of the faller and non-faller groups

| Patterns | Directions of GRF | AP GRF (times body weight) Faller (Mean ± SD) | Non-faller (Mean ± SD) |
|---|---|---|---|
| Forward Single Step | anterior (+) | 0.05 ± 0.04 (n = 2) | – (n = 0) |
| | posterior (–) | 0.15 ± 0.10 (n = 9) | 0.15 ± 0.06 (n = 10) |
| Forward Multiple Steps | anterior (+) | 0.03 ± 0.04 (n = 2) | 0.06 ± 0.04 (n = 4) |
| | posterior (–) | 0.11 ± 0.02 (n = 4) | 0.11 ± 0.05 (n = 7) |
| Backward Multiple Steps | posterior (+) | 0.28 ± 0.23 (n = 5) | 0.10 ± 0.06 (n = 5) |
| | anterior (–) | 0.08 ± 0.00 (n = 2) | 0.13 ± 0.06 (n = 7) |

multiple steps.

## DISCUSSION

During daily life, falls usually occur in both the forward and backward directions in the event of a trip or slip, which rank among the most common causes of falls and fall-related injuries in the elderly population[2]. Previous studies have reported that the occurrence of stepping is greater for backward step than for forward step[4]. In the present study, both faller and non-faller groups showed a forward single step pattern (55.3%) more than a backward single step pattern (4.8%). Therefore, the elderly of both groups seem to find single backward step to recover balance more difficult than a forward step. This reveals that most elderly might have problems falling backward more than forward because only a forward single step can recover balance during backward platform translation, while backward multiple steps were used to recover balance during forward platform translation. The results regarding history and causes of falls agree with a previous study[2] that the main causes of falls in Thailand were slipping (52.8%) and tripping (26.4%).

The results of the present study also agree with previous studies[5,9] that there is no difference in the backward step pattern in backward perturbation between the faller and non-faller groups. The elderly typically used multiple small backward steps to recover balance from backward perturbation. The use of backward multiple steps by both the faller and non-faller groups may be due to efforts to shift the body weight and maintain the center of gravity allowing more opportunity to correct for instability[9] or inability to exert visual control over foot movement[23] or less range of leg extension compared to flexion.

The comparison of the present results showed no significant differences in peak vertical GRF between the faller and non-faller groups during both forward and backward steps (Table 3). No statistically significant

**Table 6.** The step lift off time, step landing time, swing duration time, step length, step height, and step velocity of the faller and non-faller groups

| Variables | Patterns | Faller (Mean ± SD) | Non-faller (Mean ± SD) |
|---|---|---|---|
| Step liftoff time (sec) | Forward single step | 0.46 ± 0.46 (n = 11) | 0.32 ± 0.43 (n = 10) |
| | Forward multiple steps | 0.50 ± 0.49 (n = 6) | 0.39 ± 0.44 (n = 11) |
| | Backward multiple steps | 0.14 ± 0.30 (n = 8) | 0.40 ± 0.45 (n = 12) |
| Step landing time (sec) | Forward single step | 0.49 ± 0.45 (n = 11) | 0.70 ± 0.42 (n = 10) |
| | Forward multiple steps | 0.81 ± 0.37 (n = 6) | 0.64 ± 0.44 (n = 11) |
| | Backward multiple steps | 0.37 ± 0.45 (n = 8) | 0.42 ± 0.45 (n = 12) |
| Swing duration time (sec) | Forward single step* | 0.03 ± 0.01 (n = 11) | 0.37 ± 0.45 (n = 10) |
| | Forward multiple steps | 0.31 ± 0.44 (n = 6) | 0.26 ± 0.41 (n = 11) |
| | Backward multiple steps | 0.23 ± 0.40 (n = 8) | 0.02 ± 0.01 (n = 12) |
| Step length (m) | Forward single step | 0.32 ± 0.09 (n = 11) | 0.31 ± 0.09 (n = 10) |
| | Forward multiple steps | 0.25 ± 0.13 (n = 6) | 0.20 ± 0.12 (n = 11) |
| | Backward multiple steps | 0.10 ± 0.03 (n = 8) | 0.10 ± 0.04 (n = 12) |
| Step height (m) | Forward single step | 0.10 ± 0.03 (n = 11) | 0.11 ± 0.05 (n = 10) |
| | Forward multiple steps | 0.09 ± 0.03 (n = 6) | 0.07 ± 0.02 (n = 11) |
| | Backward multiple steps | 0.05 ± 0.01 (n = 8) | 0.05 ± 0.02 (n = 12) |
| Step velocity (m/s) | Forward single step* | 13.09 ± 5.69 (n = 11) | 6.41 ± 6.23 (n = 10) |
| | Forward multiple steps | 8.85 ± 7.70 (n = 6) | 6.73 ± 5.86 (n = 11) |
| | Backward multiple steps | 6.62 ± 5.09 (n = 8) | 7.74 ± 3.50 (n = 12) |

* Significant difference between the faller and non-faller groups at $p<0.05$.

difference probably reflects the small sample size that was based on group and stepping pattern even though total number of the subjects in the present study was 81 (36 fallers and 45 non-fallers). When dividing the subjects who landed clearly on the forceplate into each group (faller or non-faller) and each step pattern (single or multiple steps), the sample size per group and pattern were smaller than before classification. A further study should collect data from more subjects within each group and each pattern. It might clarify the differences of peak vertical GRF between the elderly faller and non-faller groups.

Although, the AP and ML GRFs and the vertical peak GRF during forward and backward steps indicated no significant differences between the faller and non-faller groups, the pattern of GRF and peak GRF demonstrated some characteristic differences.

During forward step, most fallers and non-fallers demonstrated a posterior direction (-) for the AP GRF (Table 5). However, 18% of the fallers had a different pattern of the AP GRF. The present results are in agreement with those of a previous study[24] that hypothesized the normal pattern is used during fall recovery. During the step landing period, the resultant GRF between the vertical and AP directions is aligned with the COM and acts upward and backward relative to the COM. The upward GRF retards the downward momentum of the COM. The backward GRF minimizes the forward velocity of the COM. The resultant GRF results in minimal angular impulse generation[24]. These results show that the reduction in forward and downward translation of the COM related to the fall occurred during the step landing period. Therefore, the consistent patterns of joint moment which were predominantly extensor (or plantar flexor) should be found during forward fall recovery in both the faller and non-faller groups[25]. However, inability to generate sufficient linear and angular impulses during the first step in older adults is consistent with the need for older adults to take multiple steps to recover balance[24].

During backward multiple steps, even though the AP GRF of fallers showed a different pattern compared to the non-fallers (Table 5), the resultant GRF between the horizontal and vertical directions in the step leg of both groups was behind the COM during backward step, possibly because all subjects in the present study were successful at recovering balance during backward step. For successful recovery from backward fall, the whole body needs to generate a forward angular impulse to neutralize backward angular momentum. Hence, the hip flexor, knee extensor, and ankle plantar flexor muscles should be dominant during backward fall recovery[25]. Data from the mean values of the major patterns of the vertical and AP GRF (Tables 3 and 5) were interpreted. The faller group had a tendency to have a longer lever arm than the non-faller group. It may cause fallers to use more muscles effort than non-fallers during backward step to recover balance. The dominant muscle groups during backward fall recovery in the fallers might have some problems.

Swing duration time of fallers was shorter than that of non-fallers, while step velocity of fallers was higher than that of non-fallers. The swing duration time has been reported to be associated with ML body motion and stability of the body on one leg[15]. When on one leg, the BOS is reduced to the area of the stance foot, loading the total body weight on the stance foot which is used as an anchor for stabilizing the body, while the stepping leg swings to prepare a new BOS. The elderly fallers had a tendency to step faster indicating they have shorter swing duration and higher step velocity than the non-fallers. Hence, we suggest that the elderly non-fallers had remarkably better stability on one leg than the fallers. Therefore, improvement of stability and ability to stand on one leg are important for the prevention of falls among the elderly.

From the finding of the step pattern, increasing the ability to move the leg in the backward direction, such as step backward training and walking backward, should be promoted in the elderly to prevent falls. The finding of the ground reaction forces, suggests that the elderly in both the faller and the non-faller groups had better ability to recover balance during forward step than the backward step. The primary muscles for stabilizing the leg during foot contact and stopping forward momentum, such as the hip extensors, knee extensors, and ankle plantar flexors, should be promoted to improve ability to prevent forward fall. Moreover, the hip flexor, knee extensor, and ankle plantar flexor muscles should be promoted to improve stepping ability to prevent backward fall. From the finding of the temporospatial characteristics, the elderly fallers had remarkably worse stability on one leg than the non-fallers. Therefore, stability and ability to stand on one leg should also be promoted in the elderly to reduce the risk of losing balance and risk of falls though balance training on one leg and weight shifting training.

In conclusion, both the elderly fallers and non-fallers showed similar stepping patterns with the forward single step pattern (55.3%) being utilized more than the backward single step pattern (4.8%). The ground reaction forces of both the fallers and non-fallers showed a similar GRF with a posterior direction of GRF being shown during forward single and multiple steps. Fallers had a higher ML GRF than non-fallers during forward and backward multiple steps. Most of the non-fallers demonstrated an anterior direction of GRF whereas more fallers indicated a posterior direction of GRF during backward multiple steps. During forward single step, the swing duration time of the fallers was significantly shorter than non-faller, whereas the step velocity of the fallers was greater than that of the non-fallers. The elderly fallers had remarkably worse stability on one leg than the non-fallers.

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