

Effects of Step Length Change on Kinetic Characteristics While Stepping Over an Obstacle From a Position of Quiet Stance in Young and Elderly Adults: A Preliminary Study

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Abstract

The aim of the present study was to investigate age-related differences in stepping behavior in response to sensory perturbations of postural balance. The participants for this study were 2 healthy elderly adults (mean age=76.0) and 2 younger adults (mean age=25.5). Subjects were asked to step over a 10 cm high obstacle at self-paced speed with the right limb to land on the primary target (normal step length) that is 10 cm in diameter. However, if, during movement, the light was illuminated, then the subject had to step on the secondary target (long step length). It was planned that the onset of the light would be prior to peak Fx of swing limb, between swing peak Fx and swing toe-off, and after swing toe-off. In the younger adults these secondary visual cues were provided at mean times of 240 ms (standard deviation (SD)=11), 402 ms (SD=13), and 476 ms (SD=88) following the movement onset. Corresponding mean times for the healthy elderly were 150 ms (SD=67), 352 ms (SD=39), and 562 ms (SD=115). Results showed great changes in both group and visual cue condition in Fx ground reaction forces and temporal events following the swing toe-off. Swing limb acceleration force (Fx) and stance peak Fx1 was much greater in the young adults compared to the older adults. Both young and older adults increased stance peak Fx2 in the visual cue condition compared to normal stepping. There was no difference in stance peak Fx2 between the visual cue conditions in both groups. Similarly, the time to stance peak Fx2 was much longer for the visual cue condition than for the normal stepping. It was not different between the visual cue conditions in the young adults, but in the elderly mid and late cue was much greater than early cue. In addition, time to stance peak Fx2 and swing and stance time were much longer in the older adults compared to the young adults for the visual cue conditions. These results suggest that unlike young adults, elderly adults did not flexibly modify their responses to unexpected changes in step length while stepping over obstacles.

Key Words: Elderly; Falls; Ground reaction forces; Sensory perturbation; Stepping.

Introduction

In order to perform daily activities an individual must be able to control balance of the body proactively (volitionally) or reactively. In proactive control, appropriate responses occur to avoid perturbations and allow uninterrupted locomotion. For example, while stepping over obstacles there is a need to continuously monitor the obstacle's location and charac-

teristics, and modulate limb trajectory to avoid obstacles in a proactive manner. Subjects appear to use many different strategies to modify and adapt gait patterns when confronted with obstacles. For example, one strategy is to identify the potential obstacles and increase toe clearance and/or change the direction of gait when objects cannot be cleared.

Applying the sensory perturbation during a challenging stepping task may be a useful tool to meas-

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ure the changes of postural response between healthy people and people with balance dysfunction. McGibbon et al (2005) showed, in fact, that individuals with balance impairment have reduced ability to stabilize locomotor patterns following an auditory sensory perturbation, compared to healthy adults, that was applied by suddenly changing the cadence of the metronome at a predetermined time. In particular, the authors concluded that both balance impaired groups (vestibular hypofunction and cerebellar pathology) had more difficulty in maintaining normal stepping pattern and a slower recovery compared to the healthy participants when the auditory (cadence) perturbation occurred.

McFadyen et al (2006) also showed that both visual and vestibular perturbations in the healthy adults caused a slower gait speed with increased foot and lateral deviations in head and trunk roll angles as well as in foot and trunk displacements during obstacle avoidance. The authors interpreted these findings as suggesting that visual information is utilized in a manner of anticipatory control which is most important for lead limb clearance. However, vestibular information does not appear to be processed the same way as the visual perturbations for obstacle crossing because vestibular perturbations to foot placement and upper body roll angles did not result in increased vertical foot clearances over obstacle.

Other investigators have used perturbations induced by the presentation of a sudden virtual obstacle while walking. For example, Chen et al (1994) has studied age-related differences when the elderly and young adults step over virtual obstacles under different available response times. They found that the amount of available response time played an important role in the success of obstacle negotiation in adults of any age. Older adults, however, were more likely to contact the obstacle than the corresponding young adults when a virtual obstacle suddenly appeared in the gait path. Mean success rates for the old were about 16% at 200 ms available response time and 92% at a 450 ms available response time before the heel-strike of

swing phase leg. The corresponding mean success rates for young adults were about 21% and 97% respectively. Thus, a reduction of available response time decreases success rate of stepping over obstacles more in older adults than in young adults.

Gait adjustments used to negotiate obstacles have been well studied in young healthy adults (Begg et al, 1998; Begg and Sparrow, 2000; Brunt et al, 1999; Chou and Draganich, 1997; 1998; Patla and Rietdyk, 1993; Patla et al, 1991; 1996). Older adults appear to use a significantly more conservative strategy to avoid obstacles during walking. Older adults showed a somewhat slower approaching speed, a significantly slower crossing speed, and decrease in step length prior to obstacle crossing (Chen et al, 1991). Older adults also appear to position both the lead and trail foot relatively farther from the obstacles compared to young healthy adults (Begg and Sparrow, 2000). This risk-related non-optimal foot placement strategy on the approach to the obstacles makes less lead foot clearance and little correction time in the event of foot contact to the obstacles (Begg and Sparrow, 2000).

It has been suggested that elderly have more difficulty in stepping over obstacles, as compared to young adults. This difficulty may be due to muscle weakness (Hurley et al, 1998; Wolfson et al, 1995) and the inability to develop torque quickly (Thelen et al, 1996) which may lead to instability and impaired stepping behavior. Ankle and knee strength for nursing home residents who had a history of falls was significantly lower than for community living elderly (Aniansson et al, 1983; Fugl-Meyer et al, 1980; Whipple et al, 1987). Furthermore, some investigators report an increased reaction time in elderly people (Chen et al, 1994; Horak et al, 1984; Spirduso, 1980), although others report either no change with aging or conflicting results (Gottsdanker, 1982; Inglin and Woollacott, 1988; Rogers et al, 1992; Stelmach et al, 1990; Woollacott et al, 1986). Increased reaction time in the elderly may be caused either by slowing in the voluntary control system itself or by the delayed and weaker postural muscles associated with volun-

tary movement (Inglin and Woollacott, 1988).

Age-related slowing of reaction time and less efficient postural response may increase the muscular force required to mount an appropriate response to perturbation while stepping. However, at the same time, the strength of skeletal muscles and torque development involved in walking decline with aging. These factors impair the effectiveness of balance control strategies in the elderly while stepping.

These previous papers have studied balance control strategies in the elderly in response to sensory perturbations while stepping. Numerous papers reported that the problems in the lateral balance stability and motion in the elderly are most frequently related with lateral falls that often follows the hip fractures (Cumming and Klineberg, 1994; Hayes et al, 1993; Robinovitch et al, 1991). Interestingly, it had been argued that lateral body stability during obstacle crossing is a good indicator of balance impairments in the elderly (Chou et al, 2003). The aim of the present study was to examine whether an unexpected change of step length would affect the ability to step over obstacles from quiet stance in healthy older adults more so than young adults.

Methods

Subjects

The participants for this study were 2 healthy elderly (mean age=76.0, standard deviation (SD)=2.8,

range=74~78) and 2 younger adults (mean age=25.5, SD=2.1, range=24~27) with no known neurological or orthopedic deficits. In order to qualify for this study, the elderly participants had to live independently in the community and were able to complete all activities of daily living. Elderly subjects were also tested on the Mini Mental Status Exam (Gallo et al, 2000), Frenchay Instrumental Activities of Daily Living (Schuling et al, 1993), Assessment of Physical Function (Gallo et al, 2000), and Berg Functional Balance Scale (Berg et al, 1989; Berg et al, 1992). The first three were questionnaire tests while the Berg Functional Balance Scale consisted of 14 basic mobility tasks. Inclusion criteria for the frail elderly group was a Berg Functional Balance Scale score > 50, a Frenchay Instrumental Activities of Daily Living Score > 50, and a Physical Function Score > 20. All participants scored greater than 24 on the Mini Mental Status Exam. The participant's characteristics for the elderly are shown in Table 1. The elderly had no neurological or orthopedic problem that prevented them from participation in the study. No elderly participants reported a history of falls within the previous 12 months. All participants signed an informed consent form prior to participation.

Equipments

Two force platforms¹⁾, embedded in a level walkway (5 m in length and 1.22 m in width), measured ground reaction forces of the stance and swing limb.

Table 1. Elderly subject characteristics

Subject	Age	Gender	MMSE ^a	BFBS ^b	FIADL ^c	APF ^d
1	74	Male	29	56	50	29
2	78	Female	28	56	56	28
Mean±SD	76.0±2.8		28.5±.7	56.0±.0	53.0±4.2	28.5±.7

^aMMSE: Mini Mental Status Exam.

^bBFBS: Berg Functional Balance Scale.

^cFIADL: Frenchay Instrumental Activities of Daily Living.

^dAPF: Assessment of Physical Function.

1) Advanced Mechanical Technology, Inc., Newton, MASS, U.S.A.

Electrical foot switches²⁾ were placed in the shoes to measure heel-strike and toe-off of the swing limb and heel-off of the stance limb. Amplified force platform³⁾ signals were sampled on-line at a rate of 1000 Hz for 2 seconds.

Procedures

The experimental setup is shown in Figure 1. For each trial subjects stood in a predetermined position with each foot on a force platform. Subjects were asked to step over a 10 cm high obstacle at self-paced speed to a visual cue. Prior to experimental trials the average position of the swing heel-strike was determined for each subject through videotape analysis. For all experimental trials two targets (10 cm in diameter) were placed on the ground to dictate the position and accuracy of swing limb heel-strike. A small red light emitting diodes was set in the center of each target. These lights dictated when and where to step. The position of the secondary target was determined through the coordinate system. If, for example, the initial position for each subject is coordinate

(0, 0) and the step length is 'radius', the position for long step length condition is coordinate (0, 2 × radius). Subjects were asked to begin walking with the right limb landing on the primary target. When the light of the primary target came on, the subject stepped over the obstacle with the right limb. However, if the light of the secondary target came on after the light of the primary target, the subject must then step towards the secondary target.

It was planned that the onset of the light would be prior to peak Fx of swing limb, between swing peak Fx and swing toe-off, and after swing toe-off. In the younger adults these secondary visual cues were provided at mean times of 240 ms (SD=11), 402 ms (SD=13), and 476 ms (SD=88) for the long stepping following the movement onset.

Corresponding mean times for the healthy elderly were 150 ms (SD=67), 352 ms (SD=39), and 562 ms (SD=115). The timing of these cues was presented in random order. That is, subjects were unaware when and where to step. Subjects completed practice trials and five successful experimental trials in each of the

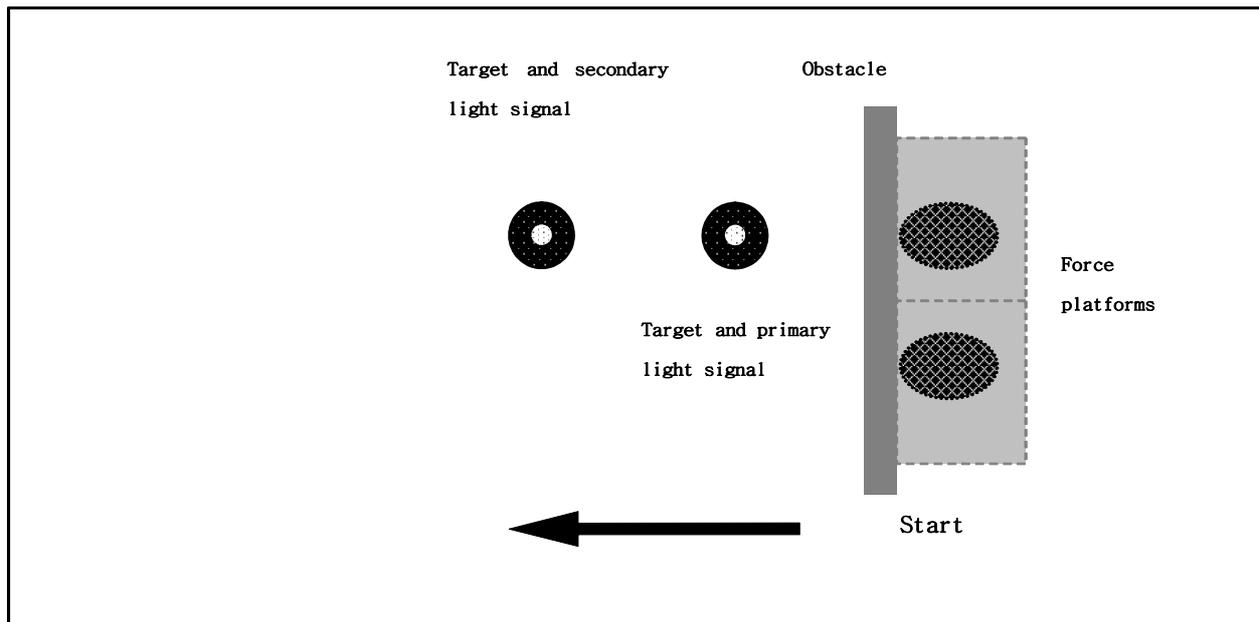


Figure 1. Experimental setup.

2) B & L Engineering, Los Angeles, CA, U.S.A.

3) BIOPAC Systems, Goleta, CA, U.S.A.

following conditions: 1) normal stepping initiated by the primary light signal 2) step forwards upon the redirection of the secondary light signal. Some trials in which the subject missed the target were repeated.

Data Analysis

The independent variables were subject group (young adults and healthy elderly) and timing of visual cue (prior to swing peak Fx (early), between peak Fx and toe-off (mid), and after toe-off (late)). Force platform measures include timing, slope and amplitude measures of anterior posterior (Fx) ground reaction forces under the stance and swing limbs. Time to swing limb toe-off, swing time, and stance time were also analyzed. Timing data were referenced from the first detectable onset of force platform activity. Means and SDs were used to compare the different conditions.

Results

Mean data for the ground reaction forces is shown in Table 2 and 3. Dependent variables that occurred

prior to toe-off such as swing peak Fx, time to swing peak Fx, slope to swing peak Fx, and time to swing toe-off did not show clear changes between conditions. However, there were group differences in the swing peak Fx. Clear changes in both group and visual cue condition were also noted for stance Fx following toe-off. Comparisons of the changes in the ground reaction force in response to three different timings of the visual cues and group difference were made.

Effect of Group and Visual Cue on the Trials Where the Target Was Missed

There was no clear group differences in the number of trials missed for step length change except for mid and late visual cue conditions. Compared to the early and mid visual cues, the number of trials missed in the late visual increased (Figure 2).

Effect of Group and Visual Cue on the Intended Velocity of Stepping

As summarized in Table 2, there were no clear group differences in the variables that are related to the intended velocity of stepping except for swing

Table 2. The peak (%BW) and slope (%BW/S) for force plate and temporal events (ms)

Dependent variables	Stepping		Long stepping	
	No visual cue	Early visual cue	Mid visual cue	Late visual cue
Swing peak Fx				
Young adults	36.6±2.6 ^a	32.1±1.4	33.1±1.6	35.5±6.5
Older adults	29.7±1.4	30.0±5.7	25.5±7.6	23.6±3.3
Slope to swing peak Fx				
Young adults	125.2±1.4	124.1±1.3	120.2±1.2	124.4±5.6
Older adults	125.1±27.1	124.2±16.4	89.1±7.7	99.3±16.2
Time to swing peak Fx				
Young adults	328.0±57.6	310.1±20.5	347.2±28.7	278.4±37.6
Older adults	240.1±28.3	263.2±5.8	252.3±54.2	228.1±30.2
Stance peak Fx1				
Young adults	43.2±9.8	50.2±16.5	43.3±14.3	43.2±12.6
Older adults	34.2±19.5	44.7±10.7	25.7±1.2	24.4±11.5
Time to swing toe-off				
Young adults	427.4±37.4	413.0±13.3	456.2±2.8	397.5±45.5
Young adults	422.5±75.5	342.1±99.6	438.1±41.2	454.6±68.3

^aMean±SD.

Table 3. The peak (%BW) for force plate and temporal events (ms)

Dependent variables	Stepping		Long stepping	
	No visual cue	Early visual cue	Mid visual cue	Late visual cue
Stance peak Fx2				
Young adults	78.0±3.8 ^a	124.1±19.6	120.0±22.5	118.3±21.6
Older adults	74.1±5.8	101.3±18.7	101.1±9.4	102.3±14.2
Time to stance peak Fx2				
Young adults	955.0±58.6	1034.2±5.1	1097.4±37.4	1033.5±3.8
Older adults	947.1±185.2	1048.2±168.6	1139.3±102.9	1149.1±133.5
Swing time				
Young adults	541.2±9.2	651.2±21.3	653.4±61.4	696.3±20.6
Older adults	515.3±102.7	801.1±147.6	879.2±218.3	911.2±150.6
Stance time				
Young adults	1121.1±10.4	1187.3±7.6	1254.4±51.7	1196.3±19.1
Older adults	1115.3±166.5	1190.2±153.7	1307.6±100.2	1349.0±183.4

^aMean±SD.

peak Fx. Swing peak Fx was much greater in the young adults compared to the older adults. In contrast, the swing limb peak Fx, time to the swing limb peak Fx, swing toe-off, and the slope to swing limb peak Fx were similar among all the conditions. However, stance peak Fx1 was greater for the young adults. In addition, stance peak Fx1 was greater for the early visual cue compared to normal stepping, mid and late visual cue. The overall mean for early visual cue for stance peak Fx1 was 11.8 %BW greater than the overall mean for normal stepping, mid and late visual cue.

Comparisons of the Changes in Anterior-Posterior (Fx2) Ground Reaction Force Responses of the Stance Limb

Coincident with the swing heel strike was a second peak acceleration ground reaction force (Fx2) of the stance limb. Stance peak Fx2 was much greater in the visual cue than normal stepping in both young and older adults. In addition, stance peak Fx2 was not different between the visual cue conditions in both the young and the elderly. Similarly, the time to stance peak Fx2 was much longer for the visual cue conditions than for the normal stepping. It was not

much different between the visual cue conditions in the young adults, but in the elderly mid and late cue was much greater than early cue.

Swing time was similar between the groups for the normal stepping, but there were big differences between the groups for visual cue conditions. Swing time in the elderly was 196.9 ms longer than in the young for visual cue conditions. As expected swing time for visual cue conditions was 237.2 ms longer than the normal stepping.

Stance time for both groups was similar in normal stepping and early visual cue, but in mid and late visual cue conditions the elderly was much greater than the young. In addition, stance time for visual cue conditions was 128.7 ms longer compared to the normal stepping. Table 3 shows means for peak force plate and temporal events.

Discussion

The primary goal of this experiment was to determine how both elderly and young subjects changed step distance while stepping over an obstacle. The unexpected onset of a light cued the

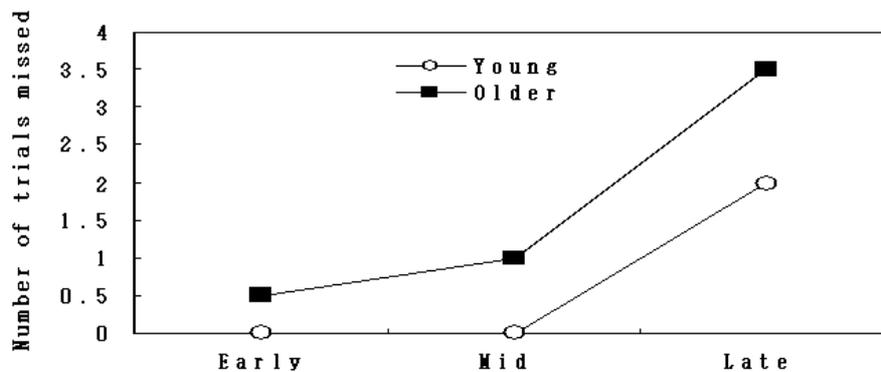


Figure 2. Mean number of trials missed on the target in both younger and older adults for long stepping.

subjects to modify their stepping characteristics. Stepping errors were greater for the elderly. In long stepping the propulsive force required to increase step length (Fx2) was considerably less for the elderly, especially for the early, mid and late visual cue. Consequently, swing and stance time greatly increased for the elderly subjects. Elderly subjects, therefore, could successfully increase step length, but compared to young subjects, with less acceleration force and over a longer period of time.

Previous studies (Breniere and Do, 1986; Breniere et al, 1987) have shown that the acceleration forces (Fx) of the swing limb determine the intended velocity of the gait initiation. This acceleration force increases with faster speed or decreases when subjects are constrained by the accuracy of the swing limb heel-strike (Breniere et al, 1987; Brunt et al, 1999). Moreover, in healthy young adults slope to swing peak Fx remains constant regardless of task conditions, i.e., gait initiation versus stepping over an obstacle. These results suggest that in both tasks subjects equally modulate the acceleration force of the swing limb to determine the intended velocity for each task.

In the present study, those variables that dictate the intended velocity of initiation did not change between normal stepping and those trials when the visual cue required change in step length. This is important as it illuminates initiation velocity as a possible strategy to ensure successful experimental trials.

However, swing limb acceleration force prior to toe-off was always less for the elderly group. Although the slope to swing limb peak Fx was similar between two groups for normal and early visual cue condition, the older adults showed 27.8% BW/s less slope to swing peak Fx for mid and late visual cue conditions. These differences of the ground reaction forces of swing limb between the young and older adults indicated that the older adults were not able to produce sufficient ankle torque to generate acceleration forces equal to those of the young adults.

The acceleration force of stance Fx1 is related to the rate of swing limb toe-off. In the present study stance limb peak Fx1 was greatly less in the older adults compared to the young adults. This decrease in the peak stance peak Fx1 paralleled an increase in the time to swing limb toe-off and therefore an increase in time preparation for stepping and toe-clearance. However, clear difference in the swing limb toe-off between two groups was not found in the present study.

After swing toe-off the center of mass of the body moves forwards and in the late swing phase it passes beyond the stance limb. During this period, there is a greater threat to the equilibrium of the system. Step length lengthening is mainly achieved by applying a larger acceleration force. The increase in push-off during late stance facilitates hip flexion. Step length is also regulated by controlling the knee

extension during foot placement phase. Swing limb heel-strike coincides with stance Fx2. In the present study, stance Fx2 was much lower for the older adults than that of the young adults. In addition, time to stance peak Fx2 and swing and stance time for the visual cue conditions were much longer in the older adults compared to the young adults. Previous study (Brunt et al, 1999) has shown that stance peak Fx2 is related to the walking speed. Thus, for fast speed stance peak Fx2 increase and time to stance peak Fx2 is reduced.

Conclusion

These results suggest that unlike young adults, elderly adults did not flexibly modify their responses to unexpected changes in step length while stepping over obstacles. Furthermore, these diminished abilities may partially account for high rates of falls in the elderly. Although the current study addressed stepping behavior in both younger and healthy older adults, it did not include all the questions that could have been asked. Future investigations will be to clarify some of the issues that current study left unresolved.

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