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Original

Kinematic and kinetic characteristics of stepping over a 10-cm-high obstacle in older adults

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Abstract

[Purpose] The purpose of this research was to clarify the common responses shared by a high-falldown-risk group of older adults and develop an exercise-learning program to prevent falls. [Subjects] Thirty-four subjects were chosen from those who use the daycare program of a nursing home at least once a week. [Methods] All subjects were categorized in longer or shorter-MSL groups. Ninety-second stepping from two force plates to a 10-cm-high box was executed under three conditions. The locus length of the COP, toe-obstacle distance, and step length were used as experimental data. [Results] The coefficient between the MSL and COP was from 0.69 to 0.73. The shorter-MSL group showed smaller COP movements in the A-P direction and a smaller toe-obstacle distance between the single stepping and stepping with the visual task and between the single stepping and stepping with the auditory task. No significant difference was noted in the step length between the two groups. [Conclusion] The shorter-MSL group was easily affected by the dual-task, suggesting that the shorter-MSL group has a high risk of falling when negotiating obstacles. Stepping exercise with the dual-task using the COP movements as a feedback index may be useful for older adults who have a smaller MSL.

Key words: COP, dual-task, stepping

Introduction

Older adults are more likely than younger adults and adolescents to experience serious physical harm such as fractured bones or to require more care if they fall down[1]. The *Nationwide Life Fundamentals Survey* conducted in 2001 by the Japanese Ministry of Welfare and Labor showed that while they represent 20 percent of the population in Japan, 28 percent of older adults reportedly become bed-ridden because of falls or bone fractures caused by falls. Older adults tend to fall down more than the young because of internal factors attributed to their body function and external factors such as the environment they are in. Some reports state that these two factors are frequently related and often result in accidents like falls[2]. The internal factors include muscle weakness of the lower extremities, diminished flexibility, poor vision, impaired sensory function, slower response time, and trauma induced by falls.

On the other hand, external factors such as small differences in the floor level, abrasion-inducing carpets, slippery bathroom floors, or obstacles on the floor can cause older adults to fall. They often experience such accidents at home after they stumble over a bump or they try to move from a static position[3]. To prevent falls, it is essential that seniors are able to step with appropriate timing, length, and height[4]. Tasks such as looking, hearing, or thinking are easy if only a single task is executed. However, when a task of body motion is added to those tasks, the aged show a greater risk of falling[5,6].

In an aging society, many intervention programs[7,8] have been developed to prevent falls, curb medical expenses, and decrease the number who need care in the future. Most of these programs consist of power rehabilitation represented by such methods as strengthening the power and improving the flexibility of the lower extremities[9]. They do not, however, focus on dual task training. Nor do they deal with a method of learning to develop physical responses that are needed for preventing falls in older adults.

Here, we measured the maximal step length (MSL), with which the walking function and fall risk could be extrapolated without the use of an expensive medical device[10,11]. The measurement gave us an opportunity to investigate the common responses of subjects who were categorized as the shorter-MSL group when stepping over an obstacle. We surveyed the impact of dual tasks on the group by asking them to execute stepping over an obstacle and use visual or auditory functions at the same time. We adopted the locus length of the center of the foot pressure (COP) as an index and a three dimensional motion analysis system for biomechanical analyses. We assumed that, compared with the longer-MSL group, the shorter-MSL group would have a shorter COP locus length in their anterior-posterior (A-P) and medial-lateral (M-L) directions, become unstable when moving to a different floor level, and be affected by executing visual and auditory tasks. The purpose of this research was to clarify the common responses shared by the high-falldown-risk group of older adults and, as a result, develop an exercise-learning program to prevent falls in the elderly.

Subjects

Subjects were chosen from those who use the daycare program at Yuyunosato Nursing Home in Ikoma City, Nara at least once a week. The sample comprised 15 males and 19 females between the ages of 66 and 81, with an average age of 71.2 years. Subjects underwent a medical history and physical examination, which focused on the musculoskeletal and neurological systems. We set up the following conditions for subjects to meet: they could walk without any assistive devices, their score on the Mini Mental State Exam was more than 25 points, they presented no problems with respiratory, circulatory, or neurological functions, and they experienced no problems with their visual and auditory systems serious enough to affect their daily lives. Subjects were briefed on the purpose of our research and submitted written consent to participate. We first interviewed them to determine their age and birthdate, and measured their weight, height, and visual functions. Subjects were instructed to wear comfortable clothing and their usual footwear during the experiments. This study was approved by Aino University Human Research Ethics Committee.

Methods

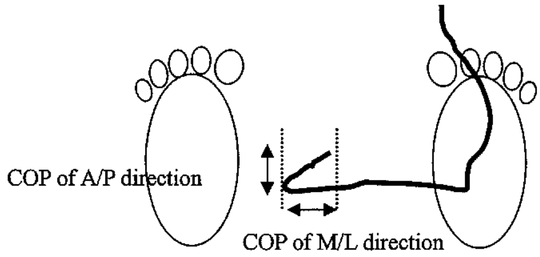
・Fall-risk classification based on the MSL

The MSL in the A-P and M-L directions was measured in 34 subjects to group them into those at either a high or low risk of falls. All subjects were rank-ordered according to the MSL. The first 17 subjects were categorized as the longer-MSL group, while the rest were listed as the shorter-MSL group. We conducted our research according to the guidelines established by Medell and colleagues[12], which state that the MSL should be measured based on the average of multiple trials.

Each subject was asked to cross their arms over their chest and step as far as possible with one leg in a given direction as directed by the examiner, and then return to the initial starting position. The MSL was measured in four directions: front, back, right, and left. Following four practice steps in each direction, one leg was tested in a set of randomly ordered directions, three steps in each direction, for a total of 12 repetitions. The MSL was defined for each direction as the average step length over a series of three trials.

・Measuring the COP of the A-P and M-L directions under the three conditions during stepping

Two force plates were set up and one wooden box (75 cm wide, 50 cm long, and 10 cm high) was placed 15 cm away from the plates. We used a rubber mat under the wooden box so that the box would not slide. The subjects repeated movement for 90 seconds, moving their dominant foot first to the box, with the other foot coming after, and moving the dominant foot and then the other back to the force plate. Each subject was asked to kick a stationary ball on the day of testing to determine foot dominance. The dominant foot was determined as the foot he/she used to kick the ball. Stepping was paced out once every four seconds with the use of a metronome. We recorded the COP on 90-second stepping in the A-P and M-L directions (Figure 1). The COP under the feet moves backwards (A-P direction) and toward the foot that is to be lifted first (M-L direction)[13,14] This shift of the COP posteriorly and toward the swing leg increases the components of the ground reaction force anteriorly and toward the stance leg. In addition, by increasing the components of the ground reaction force through the COP shift rather than through



Figue 1 A typical trajectory of the COP under the feet in anterior-posterior and medial-lateral directions
The COP under the feet moves backward and toward the foot that is to be lifted first. In this figure, the left leg is for swing and the right one is for stance.

movement of the center of mass (COM), the step-initiation motor program generates the initial momentum necessary for taking a step before the COM moves forward off the base of support[15].

Ninety-second stepping was executed under three conditions: single stepping, stepping with a visual task, and stepping with an auditory task. The order of the three trials was random, and at least three days elapsed between each trial. In addition, before the actual survey, the subjects participated in a preliminary practice once for every 90-second stepping trial.

・Stepping with visual and auditory tasks

On stepping with the visual task, a 30-cm-long and 49-cm-wide computer display was positioned two meters in front of the subject at the height of his/her eyes. We presented one image of five animals (dog, cat, elephant, giraffe, and pig) every five seconds using PowerPoint and asked each subject to identify them. Stepping with the auditory task consisted of the sound of five musical instruments (harmonica, trumpet, guitar, piano, and harp) produced by means of a PowerPoint system on the same computer used in the stepping with visual task. The subjects were requested to identify each instrument. The names of the animals and instruments for the visual and auditory tasks were given to the subjects beforehand.

・The toe-obstacle distance and step length

The Um-CAT Three Dimensional Motion Analysis System (Unimec Corporation) is comprised of two cameras. Its main part was utilized to measure the toe-obstacle distance between the obstacle and foot and the step length that the subjects used when they stepped over an obstacle.

Reflective markers, 1.5 cm in diameter, were placed on the upper front edge of the 10 cm obstacle. Markers were placed on the dominant foot, the lateral sole of the shoe directly below the fifth metatarsal head, and on the most posterior-lateral aspect of the sole of the shoe at the heel. On the non-dominant foot, a marker was placed on the sole of the shoe directly below the first metatarsal head.

The toe-obstacle distance was defined as the minimum vertical clearance between the top of the obstacle and marker placed on the lateral sole of the shoe directly below the fifth metatarsal head of the lead foot as it passed over the top of the obstacle. The step length was defined as the horizontal distance between the heel marker on the lead foot at heel strike after crossing the obstacle and the trail foot marker on the lateral sole of the shoe directly below the first metatarsal head at heel strike prior to the obstacle. For both the toe-obstacle distance and step length, average scores during 90-second stepping were calculated for data analysis.

・Data analysis

Thirty-four subjects were ranked according to the MSL length and divided into two groups: 17 persons with the longer MSL belonged to the longer-MSL group, and the other 17 persons with the shorter one belonged to the shorter-MSL group. To confirm that they were properly categorized in accordance with the MSL length, t-tests were utilized to compare differences in values presented by the longer-MSL group with those by their shorter-MSL counterparts. The coefficient of variation was used to compare the COP of the A-P and M-L directions between the longer- and the shorter- MSL groups. Additionally, a simple regression line was used to confirm the relationship visually. Two-factor factorial ANOVA with repeated measures was used to compare the COP of the A-P direction, COP of the M-L-direction, foot clearance and step length between the longer- and shorter-MSL groups on the single stepping, stepping with the visual task, or stepping with the auditory task, respectively. The factor condition refers to the single stepping and stepping with multiple-task trials. Significant differences in effect were defined as those at the $P<0.05$ probability level. When significant effects were identified, post-hoc Tukey tests were performed to identify specific influences. Excel statcel2, add-in forms on Excel 2nd ed., was used for all statistical analyses.

Results

・Correlation between the MSL and COP in the A-P and M-L directions (Figure 2)

To identify correlations between the MSL and COP during stepping, we measured all subjects' MSL and recorded the COP in the A-P and M-L directions when a subject lifted his/her dominant foot up from the 10-cm-high box. The result was a coefficient of 0.69 between the MSL and COP in the A-P direction, while we recorded a coefficient of 0.73 between the MSL and COP in the M-L direction. The relationship between the MSL and COP was categorized by the A-P and M-L directions to obtain a recurrence curve.

Based on the MSL, we divided the 34 subjects into two groups: a longer-MSL group, and a shorter-MSL group. The details of each subjectin these groups are shown in Table 1. The longer-MSL group consisted of nine males and eight females with an average MSL value of 58.2±7.4 cm. In the shorter-MSL group, there weresix males and eleven females, with an averageof 49.1±13.7 cm. The results of t-tests revealed a significant difference between these two groups.

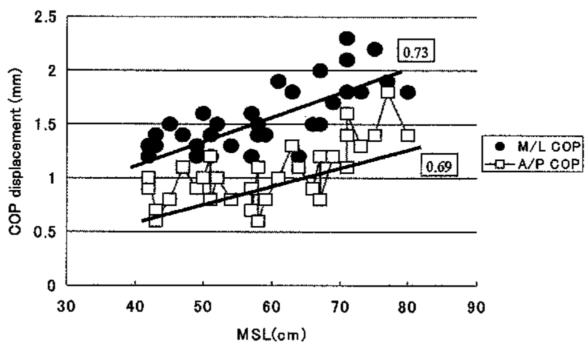


Figure 2 Correlation between the MSL and COP in the medial-lateral (upper line with black circle) and anterior-posterior (lower line with white square) directions

Table 1 Grouping based on the MSL and its characteristics

	Longer-MSL group (n=17)	Smaller-MSL group (n=17)
Male (n)	9	6
Female (n)	8	11
Age (yr)	68.8±4.2	69.6±5.9
Weight (kg)	58.3±6.9	66.7±6.2
Height (cm)	159.4±2.1	161.5±1.7
Mean MSL (cm)	58.2±7.4	49.1±13.7

・The COP in the A-P and M-L directions on single stepping, stepping with the visual task, and stepping with the auditory task (Table 2)

Each of the longer- and shorter-MSL groups was asked to participate in single stepping, stepping with the visual task, and stepping with the auditory task. Their COP in the A-P and M-L directions was tracked to detect differences between the two groups. Each group was also observed to see if there was any difference in the COP on single stepping, stepping with the visual task, and stepping with the auditory task. Between the two groups, significant differences were noted in the COP except for on single stepping. The longer-MSL group demonstrated no significant difference in these three trials. On the other hand, the group with a shorter-MSL showed a significant difference in the COP of the A-P direction between single stepping and stepping with the visual task, and between single stepping and stepping with the auditory task. However, no significant difference was noted in the COP in the M-L direction.

・The toe-obstacle distance and step length on single stepping, stepping with the visual task, and stepping with the auditory task (Table 3)

For the longer- and shorter-MSL groups, we measured the toe-obstacle distance between the points of the foot sole that passed over the box on stepping while checking the stride. The two groups showed a significant difference in the toe-obstacle distance when comparing the single stepping vs. stepping with the visual task and single stepping vs. stepping with the auditory task. However, no significant difference was noted in the step length between the two groups.

Table 2 COP displacements in anterior-posterior and medial-lateral directions under the three conditions during stepping (Mean values±S. D.)

Dependent variable	Longer-MSL group Mean ±S. D. (mm)	Shorter-MSL group Mean ±S. D. (mm)	p-value
A/P displacement of COP	16.3±5.9	14.3±6.1	NS
A/P displacement of COP with visual task	17.4±8.3	12.9±5.6	<0.05
A/P displacement of COP with auditory task	16.8±5.0	12.3±6.1	<0.05
M/L displacement of COP	15.9±7.14	12.8±5.2	<0.05
M/L displacement of COP with visual task	14.7±3.9	10.2±2.3	<0.01
M/L displacement of COP with auditory task	14.1±4.4	11.6±3.8	<0.05

Table 3 Toe-obstacle distance and step length under the three conditions during stepping (Mean values±S. D.)

Dependent variable	Longer-MSL group Mean±S. D. (cm)	Shorter-MSL group Mean±S. D. (cm)	p-value
Toe-obstacle distance	12.4±2.9	12.1±3.1	NS
Toe-obstacle distance with visual task	13.8±2.2	11.0±2.8	<0.05
Toe-obstacle distance with auditory task	13.5±3.4	11.3±2.5	<0.05
Step length	56.7±9.2	53.5±8.8	NS
Step length with visual task	52.1±10.7	49.9±9.1	NS
Step length with auditory task	53.4±10.5	48.5±8.3	NS

Within each group, no significant difference both in the toe-obstacle distance and step length was detected.

Conclusion

As community-dwelling older adults often spend much of their time indoors, numerous falls occur indoors[16]. When we think about Japanese housing construction, living spaces for many older adults are extremely narrow, and gait initiation and stopping are key components of daily life. This situation may be one reason for falls among the elderly[17]. Furthermore, age-related decreases in physiological function[18], fear of falling[19], deteriorating sensorimotor control of balance[2], difference in physiological function between reality and imagination[20], the load of dual-task conditions like watching and thinking during walking[5], etc, will make the initial gait more difficult. We measured the MSL, which is reported usefully in determining gait ability and fall risks, and confirmed correlations between the MSL and COP of the A-P and M-L directions during stepping.

As we showed in Figure 1, we noted a correlation between the MSL and COP in both directions. The COP of the M-L direction showed a slightly stronger correlation with the MSL than that of the A-P direction. Chou et al.[21,22] also investigated the relationship between the COP and COM when stepping over obstacles among older adults, and reported that the M-L displacement and peak M-L velocity during obstacle crossing could be used to better detect dynamic instability.

In the first step from static standing, inhibition of the soleus followed by activation of the tibialis anterior in both the swing and stance legs will occur at the beginning. Then, the COP moves backward and toward the foot that is to be lifted first. This shift of the COP posteriorly and toward the swing leg increases the components of the ground reaction force anteriorly and toward the stance leg[15].

Compared to the longer-MSL group, the shorter-MSL group showed a smaller COP shift in the A-P and M-L directions. This suggests that shorter-MSL group members may not be able to lift their foot sufficiently to clear the obstacle, and so the risk of foot contact with the obstacle or tripping may increase. An increase in the toe-obstacle distance may represent a more conservative strategy for avoiding contact of the trail foot with the obstacle. Chou et al.[21] reported that, in young adults, a shorter toe-obstacle distance results in reduced hip, knee, and ankle flexion, and the trail foot vertical toe clearance as obstacles of various heights were crossed. In their study, a shorter toe-obstacle distance was also associated with a greater risk of trail foot contact with the obstacle. A decreasing hip abductor force in the shorter-MSL group may be concerned with decreasing COP movement in the A-P and M-L directions. Chang et al.[23] studied the relationship between the hip abductor rate of force development and M-L stability in older adults, and reported that the hip abductor correlated with the performance of clinical tests that challenge lateral stability.

To step over an obstacle without tripping, lifting the lead foot to an adequate height is performed before shifting the COP forward. Therefore, there may be no significant difference in COP movement in the A-P direction between the two groups. There was no significant difference between the two groups in the step length within any three trials, but in the toe-obstacle distance within the visual and auditory tasks, there was a significant difference. This also explains the fact that the shorter-MSL group intentionally lifted their lead foot to an adequate height without trying to carry their body forward.

As they could watch their step on single stepping, there was no significant difference in the toe-obstacle distance between the two groups. The longer-MSL group showed a greater COP shift in the A-P and M-L directions during stepping, so they may have a more favorable physical function in terms of balance than the shorter- MSL group. The longer-MSL group could step forward without watching their step in the dual-task condition, but the shorter-MSL group was influenced by the additional visual and auditory tasks. Therefore, there was a significant difference in the toe-obstacle distance between the two groups in the visual and the auditory tasks. Furthermore, when visual and auditory tasks were added to stepping, there was a significant difference in COP movements in both directions between the two groups. This is because the shorter- MSL group tried to retain their center of gravity over the base. The longer-MSL group may have been able to briefly switch their attention to stepping when negotiating the obstacle while answering in the dual-task. It is difficult to confirm this without measuring the ground reaction force and COM.

The shorter-MSL group showed smaller COP movements in the A-P and M-L directions than the longer MSL-group, and was easily affected by the dual-task, visual and auditory tasks; therefore, the shorter-MSL group may have a high risk of falling when negotiating obstacles. Stepping exercise with the dual-task using COP movements as a feedback index may be useful for older adults who have a small MSL.

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