

Relationships between gait properties on soft surfaces, physical function, and fall risk for the elderly

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ABSTRACT

The plantar aspect change caused by contact with soft surfaces creates and unstable gait and increases the risk of falling, especially in the elderly. This study aimed to analyze gait property by three-dimensional motion analysis on soft and normal surfaces and to clarify the relationship with physical function and fall risk. Twenty-four older people aged 65 - 88 years old and living independently without any assistive device (7 men, 17 women) performed 5 m of walking with own maximal speed on normal and soft surface walkways. The soft surface walkway used was a low rebound urethane foam mattress. The three-dimensional kinematic gait analysis by sixteen anatomic points was used to evaluate gait property on both walkways. The gait property on soft surfaces tended to be swinging up and down in each joint and to largely lean left and right as compared with the normal surface. Moreover, it tended to decrease in a step length and to increase in a step width. All gait parameters on soft surfaces correlated significantly with functional reach. On the other hand, that on normal surface correlated significantly with leg strength. Gait properties on soft surfaces which changes in plantar aspect during foot contact differs from those on normal surfaces. Walking on soft surfaces may cause an unanticipated inverted pendulum sway supporting a foot contact point because of the disturbance by a sagging walkway; in short, requiring more effort to keep a body balanced. In conclusion, gait on the

soft surfaces requires balance ability (functional reach) rather than leg strength.

Keywords: Three-Dimensional Kinematic Analysis; Leg Strength; Balance

1. INTRODUCTION

Prolongation of independent life for the elderly and control of the marked increased rate of medical expenses are key tasks in Japan, which has become a super aging society. Mobility is one of the most basic skills necessary to keep an independent daily life. Their falls bring about serious problems related to the decline of quality of life, such as the bedridden state caused by bone fractures, and the decline of activity range and volume due to the fear of falling. It was reported that more than one third of the elderly over 70 years of age living independently in communities experience a fall at least once a year, and their fall occur chiefly during walking or transfer movement [1].

A fall is the result of exceeding the limit of one's own postural control from any cause. Age-related decline in the physical functioning of visual, locomotion, and nervous system makes stability during walking difficult. However, a fall during walking rarely occurs without some sort of trigger, except for those who fall due to dizziness or syncope. Most falls involve a trigger such as a misstep or slip. The risk of falling increases when a person lacks the ability to adapt to surface environment changes (e.g. tilt, difference in floor height, slipperiness, and hardness change) [2-4].

Many mobility tests that evaluate fall-related physical fitness have been proposed in the previous studies: 10-m

Walking Test [5], Figure Eight Track Walking Test [6], Timed Up and Go Test [7], and Tandem Gait Test [8]. These tests are useful to evaluate the independence of daily living. However, mobility on stationary surfaces may not reflect the ability to avoid a fall, because the fall risk relates to the adaptability to variations in walking environments, as previously stated.

On the other hand, an obstacle walk test has been proposed as an irregular surface condition [9,10]. It is a useful test to evaluate avoiding a stumble that induces a fall. However, the participants can see the obstacles placed in test walkways before they begin to walk, and are therefore more likely to maintain stability.

There has been little research on the gait of elderly people on varied surfaces. Therefore, a soft surface, such as a mattress, is considered to be adequate for the gait analysis of elderly individuals because the change of plantar aspect when contacting the surface increases the risk of falling. When an elderly person walks on soft surfaces, the plantar aspect changes and they are required to control the sway of their body by using somatosensory input through plantar and postural reflexes. It is much more difficult for an individual to maintain their balance when walking on a softer surface compared to a normal walkway.

Considering a fall process, it will be important to examine the body's stability during walking in the above walkway condition. It was hypothesized that gait property on soft surfaces differs from that under normal conditions, and is related to different physical functions, adding that walking on soft surfaces reflects more the degree of fall risk and independence of daily living. If physical functions related to gait properties on both walkway conditions differ, it is necessary to review the exercise and physical functions to prevent falls.

This study aimed to analyze gait property by three-dimensional motion analysis on soft and normal surfaces and to clarify the relationship between physical function and fall risk.

2. METHODS

2.1. Participants

Seven older men (Age: 72.4 ± 5.2 years, Height: 162.6 ± 6.2 cm, Body mass: 65.7 ± 13.0 kg) and seventeen women (Age: 74.6 ± 7.5 years, Height: 148.9 ± 7.3 cm, Body mass: 52.2 ± 9.8 kg) living independently without any assistive devices in the community dwelling participated in this study. There was no significant difference in the mean ages of the sexes ($t(22) = 0.670$, $p = 0.510$). Informed consent was obtained from each participant after a full explanation of the experimental project and its procedure. This study was approved by the Ethics Committee on Human Experimentation of Faculty of Educa-

tion, Kanazawa University.

2.2. Experimental Device

For the three-dimensional kinematic gait analysis, sixteen passive markers (15-mm diameter reflective, adhesive styrofoam) were attached bilaterally to the following anatomic landmarks; acromion, olecranon, ulnar head, anterior iliac crest, greater trochanter, knee, ankle and fifth metatarsal. Marker trajectories were recorded two strides after one stride from onset of walking at 60 Hz by six digital camcorders (MA-2000, Anima, Japan). Tridimensional reconstruction of the marker trajectories was performed by means of a reference system (leveling wires with equally spaced markers, forming a cube 3.0 m in length, 1.70 m in height, and 1.30 m in width) in order to calibrate the experimental set.

Gait parameters were selected as follows: mean walk velocity, standard deviations of the movement distance of joint points (acromion, knee, and ankle) in the frontal and sagittal directions [11]. Further analysis was performed on only the right joint points because the movement distance between the right and left joints had a 0.95 correlation.

2.3. Procedure

Using within-subjects design, the participants performed a 5-m walk at their own maximal speed on normal and soft surface walkways. The trial order on both walkway conditions was allocated randomly, and the rest among the trials was set 10 minutes. The participants walked on a low rebound urethane foam mattress (Blance mattress, Achilles, Japan; width: 970 mm, depth: 603 mm, thickness: 80 mm) spread on the soft surface walkway. The toughness of mattress was 75 N and the ratio of renaturation was 92%.

2.4. Falls Risk Assessment Score and Independent of Daily Living Score

Fall risk was estimated using a fall risk assessment questionnaire [4-12]. This consisted of eight risk factors (gait deficit, balance deficit, muscle weakness, disease, medication use, environment, visual and hearing deficit, and fall fears: 15 items). Participants answered all questions with a dichotomous scale (yes or no). The response with a high risk category for each question was considered to be a "high-risk response", and persons scoring over five points were judged to have a high fall risk.

Independence of daily living was estimated from the view point of physical function level by falls efficacy scale [13] and activity of daily living (ADL) test [14]. The former consists of 13 items common to daily living, and participants were evaluated regarding their confidence with these items on a scale of one to ten. The ADL

test consisted of 12 items representing ADL domains of walking ability, changing and holding posture, balance, and muscular strength and dexterity (manual activity).

2.5. Tests of Leg Function

Tests of leg function were selected from leg strength and dynamic balance ability which related to mobility/transfer movement and posture control ability: isometric muscle strength tests of toe flexion, knee extension, and hip flexion joints in the former, and a functional reach test in the latter. Isometric muscle strength tests were performed twice for both legs using a hand held dynamometer (μ TAS F-1, ANIMA, JAPAN). A mean of a higher value in both legs was used as maximal strength in each joint. Plantar flexion was measured in long sitting position, and the others were measured in sitting position. Functional reach was measured by using an elastic stick [15]. Each participant maximally extended the dominant hand from an upright posture while touching the top of an elastic stick fixed at dominant acromion height on the wall. They pushed and shortened the elastic stick by extending the dominant hand and the shortened distance of the elastic stick was measured.

2.6. Data Analysis

An unpaired t-test was used to reveal sex differences in the fall risk assessment score and independence of daily living score. Two-way ANOVA (sex \times walkway condition) was used to reveal the difference of gait parameters between both surface conditions. Pearson's correlation coefficient was calculated to clarify the relationships between gait parameters under both walkway conditions, fall risk score, independence of daily living score, and leg function. A probability level of 0.05 was indicative of statistical significance.

3. RESULTS

Table 1 shows sex differences of fall risk scores, independence of daily living scores, and leg function. There were no significant sex differences in all parameters. All effect sizes by Cohen's *d* were less than moderate values ($d < 0.68$).

Figure 1 shows exemplification of the gait pattern analyzed by joint point trajectories in the frontal and sagittal directions. The gait properties on a soft surface tended to swing up and down in each joint and to lean to the right and left directions significantly as compared with the normal surface. Moreover, it tended to decrease with a step length and to increase with step width.

Table 2 shows the result of two-way ANOVA (sex \times walkway condition) regarding gait parameters. There were significant walkway condition effects in all parameters. Walk velocity on soft surface significantly de-

creased, and body sway in the right-left and up-down directions significantly increased. Effect sizes between walkway conditions by sexes were over 0.5 in all parameters. In particular, the effect of the magnitude of the standard deviation of movement distance in the sagittal direction was relatively high (1.2 - 5.2).

Table 3 shows the correlation coefficients among gait parameters, fall risk score, and independence of daily living score by sexes. Walk velocity on the soft surface correlated significantly with fall efficacy scale and ADL score in both sexes.

Table 4 shows the correlation coefficients between gait parameters and leg functions by sexes. All gait parameters, except for standard deviation of movement distance in frontal direction at acromion and knee in males, on soft surface correlated significantly with functional reach in both sexes. On the other hand, those on normal surfaces tended to correlate significantly with leg strength.

4. DISCUSSION

This study examined whether the gait properties and their relationship with the fall risk score and leg functions differ between those on the soft surface which changes the plantar aspect during foot contact and on the normal surface.

Takenaka and Uechi [16] reported that sex differences were not found in walking velocity and fall self-efficacy scale for people 61 - 91 years of age. In previous studies, the findings of sex difference on fall incidence were not always agreement. Some researchers reported that they were higher in women than in men [4,17,18], but others reported that there was no significant difference [19,20]. Physical fitness level varies among individuals because it does not only relate to sex and aging, but also relates to various factors such as chronic disease, physical activity and cognition function. There were no significant sex differences in age, fall risk score, independence of daily living score, and leg strength in this study. The effect sizes by Cohen's *d* in fall risk and ADL score, and leg strengths were moderate (0.40 - 0.68), and the sex difference in these parameters will be found in studies with a larger sample size.

The standard deviations of movement distance in frontal and sagittal directions in this study evaluate the degree of a joint sway. Walking velocity and body stability on soft surface decrease because the walkway sinks down during foot contact. Body sway of acromion in the frontal direction on soft surface was larger than that of knee and ankle joints. It is inferred that walking on a soft surface causes an unanticipated inverted pendulum sway supporting a foot contact point because of the disturbance by the sagging walkway. That is, walking on the soft surface required to keep the body in balance. On the other hand, body sway in the sagittal direction was larger

Table 1. Sex differences of fall risk score, independence of daily living score, and leg muscle functions.

		Male (n = 7)		Female (n = 17)		t	ES
		M	SD	M	SD		
Fall risk score	point	3.9	2.6	2.9	2.2	0.9	0.40
Fall efficacy scale	point	122.1	12.3	122.5	10.4	0.1	0.04
ADL score	point	29.7	4.6	26.6	6.0	1.2	0.55
Toe flexion strength	kg	5.6	3.0	4.1	2.0	1.5	0.68
Knee extension strength	kg	17.0	7.3	14.1	3.7	1.3	0.57
Hip Flexion strength	kg	23.1	11.3	19.1	6.4	1.1	0.50
Functional reach	cm	32.3	6.6	32.2	5.6	0.0	0.00

There were no significant sex differences in any parameters.

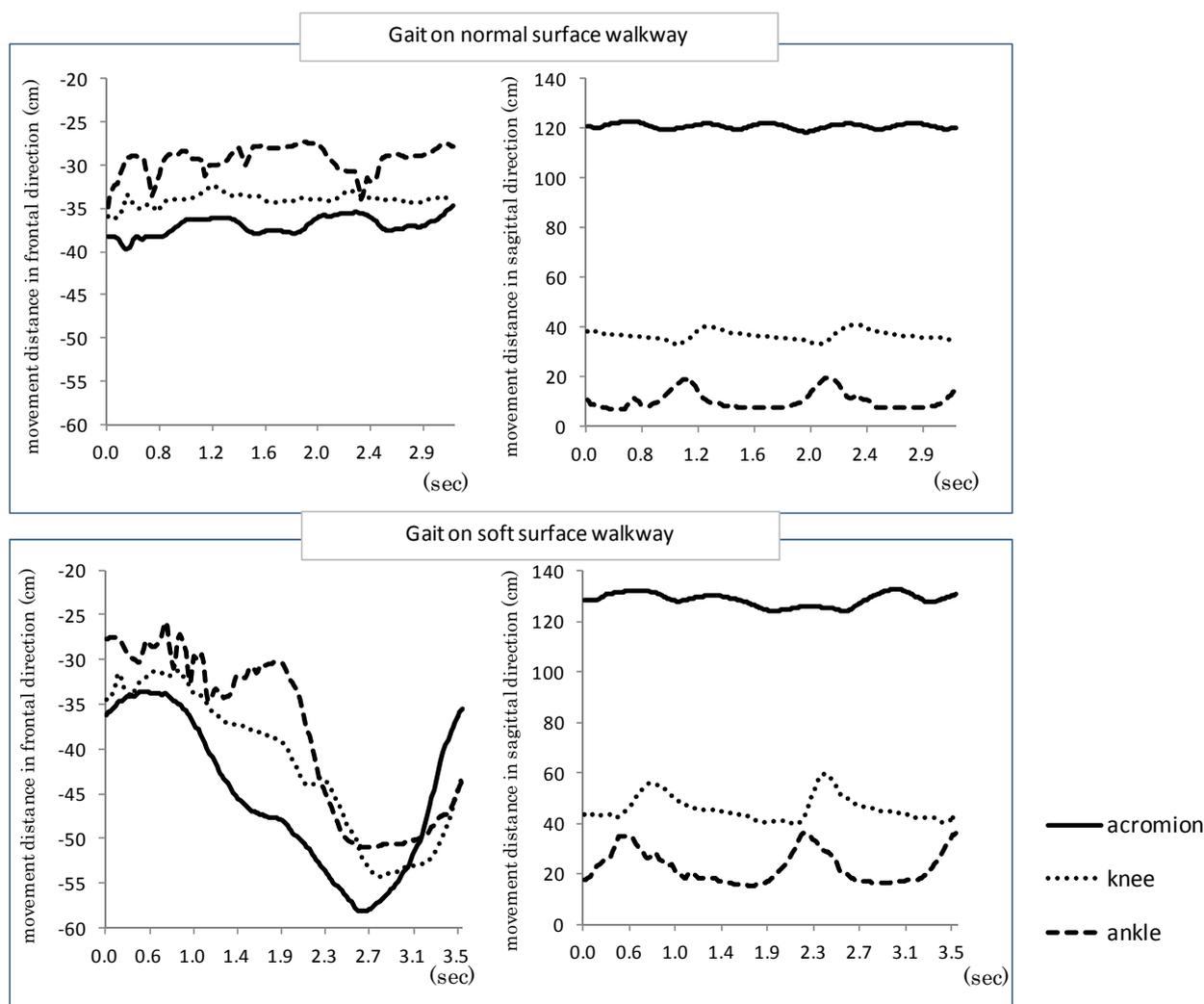


Figure 1. Exemplification of gait pattern analyzed by movement distance of 8 joint points (only right side) on the both surface conditions. Upper panel: normal surface walkway, Lower panel: soft surface walkway.

in the knee and ankle joints than in acromion. A sagging walkway by a foot contact makes the whole body sway to downward. However, body sway at acromion tended

to be small as compared with that at knee and ankle joints. It is inferred that walking on soft surface required higher elevation of the foot during the swing phase.

Table 2. Two-way ANOVA of gait parameters between the both walkway conditions by sexes.

	Soft surface				Normal surface				Two-way ANOVA			Effect size between both walkway conditions	
	Male		Female		Male		Female		sex	walkway condition	inter-action	Male	Female
	M	SD	M	SD	M	SD	M	SD	F	F	F		
Walk velocity (cm/s)	67.3	18.1	72.0	19.6	93.5	17.8	90.4	38.5	0.0	11.0*	0.3	1.6	0.6
Standard deviation of movement distance in frontal direction (cm)													
acromion	4.1	1.9	3.4	1.7	2.6	0.7	2.1	0.8	2.3	14.8*	1.3	1.1	1.0
knee	2.9	1.0	2.6	1.8	1.7	0.7	1.8	0.9	0.2	5.8*	0.2	1.5	0.6
ankle	3.9	1.3	2.9	2.0	2.1	0.7	2.1	1.0	1.1	7.8*	1.2	1.8	0.5
Standard deviation of movement distance in sagittal direction (cm)													
acromion	1.9	0.5	1.7	0.7	1.3	0.4	1.0	0.2	1.7	14.7*	0.0	1.5	1.2
knee	3.3	0.5	3.4	0.7	1.4	0.2	1.3	0.3	1.0	337.1*	2.2	5.2	4.2
ankle	6.5	1.1	6.3	0.9	4.9	0.9	4.1	0.7	2.1	105.0*	1.8	1.8	2.8

*p < 0.05.

Table 3. Correlation coefficients among gait parameters, fall risk score, and independence of daily living score.

	Male						Female					
	Soft surface			Normal surface			Soft surface			Normal surface		
	Fall risk score	Fall efficacy scale	ADL	Fall risk score	Fall efficacy scale	ADL	Fall risk score	Fall efficacy scale	ADL	Fall risk score	Fall efficacy scale	ADL
Walk velocity (cm/s)	-0.43	0.78*	0.76*	-0.13	-0.09	0.24	-0.33	-0.65*	0.58*	0.08	0.14	0.33
Standard deviation of movement distance in frontal direction (cm)												
acromion	-0.16	0.13	0.51	0.40	-0.45	-0.43	0.19	0.16	-0.16	0.07	-0.34	-0.35
knee	-0.27	0.16	0.49	0.22	0.02	0.12	-0.26	0.21	0.02	0.01	0.03	0.02
ankle	-0.10	0.64	0.22	-0.32	-0.38	0.22	0.06	0.23	0.10	-0.04	0.07	-0.03
Standard deviation of movement distance in sagittal direction (cm)												
acromion	0.72	-0.17	-0.42	0.52	0.03	0.14	-0.01	0.26	-0.01	0.04	0.19	0.51*
knee	0.74	0.14	-0.39	0.19	0.34	-0.11	-0.21	0.19	0.08	-0.35	0.40	0.13
ankle	0.35	-0.13	0.18	0.30	0.45	0.11	-0.23	0.49*	0.41	-0.43	0.65*	0.74*

*p < 0.05.

Moreover, all correlations of gait parameters between both walkways were not high. Thus, walking properties on both walkways may be affected by different physical functions.

Significant correlations were not found between gait parameters and fall risk score. However, the independence score of daily living correlated significantly with walking velocity on a soft surface in both sexes and the sagittal direction sway of the ankle joint on a normal

surface in females. Nine participants in this study were identified to have a high fall risk by cut-off score (5 points) (37.5%), and the others were lower than 3 points. Fall risk scores involve not only physical function such as walking ability, leg strength, and balance ability, but also the other factors such as medicine, environment, personality, visual and hearing problems, and fear of falling [4,12]. From the present results, gait parameters may reflect mainly physical function factors. Meanwhile,

Table 4. Correlation coefficients between gait parameters and leg muscle functions.

	Male								Female							
	Soft surface				Normal surface				Soft surface				Normal surface			
	Toe flexion	Hip flexion	Knee extension	FR	Toe flexion	Hip flexion	Knee extension	FR	Toe flexion	Hip flexion	Knee extension	FR	Toe flexion	Hip flexion	Knee extension	FR
Walk velocity (cm/s)	0.02	0.18	0.32	0.76*	0.54	0.73	0.59	0.69	0.42	0.02	0.05	0.49*	0.48*	0.26	0.07	0.35
Standard deviation of movement distance in frontal direction (cm)																
acromion	-0.26	-0.11	0.30	-0.45	0.24	0.32	0.30	0.30	-0.45	-0.35	-0.35	-0.64*	0.18	-0.02	-0.15	0.34
knee	-0.47	-0.45	-0.05	-0.49	0.49	0.81*	0.72	0.23	-0.31	-0.13	-0.05	-0.48*	0.49*	-0.21	-0.15	0.27
ankle	-0.52	-0.39	-0.20	-0.81*	0.35	0.53	0.48	-0.12	-0.26	-0.02	-0.06	-0.48*	0.49*	-0.37	-0.29	0.11
Standard deviation of movement distance in sagittal direction (cm)																
acromion	-0.08	0.19	0.30	-0.76*	0.44	0.84*	0.83*	0.73	-0.31	-0.15	-0.19	-0.50*	0.64*	-0.12	-0.20	0.17
knee	-0.07	0.14	0.13	-0.77*	-0.11	-0.41	-0.37	0.22	0.15	0.18	-0.22	-0.52*	-0.37	-0.07	-0.22	-0.50
ankle	-0.08	0.22	0.28	-0.78*	0.08	0.24	0.12	0.35	0.43	0.13	-0.10	-0.50*	0.48*	-0.06	0.48*	0.18

*p < 0.05, FR: functional reach.

the independence score of daily living was composed of item groups related closely to physical function factors [16,21]. Hence, it may have shown relationships with gait parameters on both surfaces. However, it is noted that the gait parameters with significant correlations differed between both walkway conditions. Potter *et al.* [21] reported that a relationship was found between Barthel ADL score and walking speed. However, this relationship depends largely on the physical fitness level of the older population. Because walking five meters on a normal surface was an easy task for the elderly in this study, it is hard to attribute individual differences in gait by their physical fitness level. Therefore, it may have shown a poor relationship with the independence score of daily living.

Conversely, because walking on soft surface poses high difficulty, a significant relationship with walking velocity may have been found. Means [9] and Means and O'Sullivan [22] reported that walking at a high difficulty level such as navigating an obstacle is superior in the improvement ratio of physical function to walking normally for older people living in community-dwelling. Therefore, walking on a soft surface walkway may be effective as exercise for fall prevention. In addition, those displaying greater ankle movements in the sagittal direction on a normal surface tended to have a higher independence score of daily living. Foot height during the swing phase decreases with age and physical function decline [23]. In this study, the ankle movement of the sagittal and frontal directions in the normal surface correlated with toe flexion strength in females, thus it may important to improve toe flexion strength for the inde-

pendence of daily living. Moreover, gait parameters on the normal surface in females, as compared with that on the soft surface, correlated with leg strength. This suggests that the greater movement of joint points during normal walking is affected by leg strength. These results may mean that persons with superior leg strengths walk forcefully on a normal surface.

On the other hand, almost gait parameters on soft surfaces correlated with a functional reach test in both sexes. This test was proposed to evaluate dynamic balance for older people [24]. As stated above, walking on a soft surface which prolonged the swing phase (the one-leg support phase) requires better balance ability. Walking on a low rebound urethane foam mattress makes it difficult to kick the ground when beginning walking and to elevate a leg due to soft surface. In case of normal walking, forcefully kicking the ground contributes to gain rapid and forceful movement. However, forcefully kicking the ground on the soft surface is needed large balance ability. Because the ankle movement in the sagittal direction on a soft surface correlated positively with functional reach, persons with superior functional reach may be able to elevate foot during swing phase. In fall prevention exercise schools, it is recommended to improve iliopsoas and femoral muscles to avoid stumbling over an obstacle [25,26]. However, it will also be important to propose exercise to positively move the center gravity of the body. Such exercises include the functional reach action which helps to keep body stable while walking on an irregular surface.

Further studies will be examined to clarify motion properties using kinematic analysis of other fall trigger

actions such as slips and missteps which require a stepping strategy.

5. CONCLUSION

In conclusion, gait properties on soft surfaces which change the plantar aspect during foot contact differ from those on a normal surface. Body sway of the acromion in the frontal direction on a soft surface is larger than that of knee and ankle joints. Walking on a soft surface may cause an unanticipated inverted pendulum sway supporting a foot contact point because of the disturbance by the sagging walkway. Gait on the soft surface requires balance ability (functional reach) rather than leg strength.

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