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Case Study

Preliminary gait analysis of frail versus older adults

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Abstract. [Purpose] This study aimed to verify the usefulness of an inertial measurement unit and compare the gait of frail and robust older adults. [Participants and Methods] Six participants (three males and three females) in their 80s were diagnosed as frail or robust according to Japanese Cardiovascular Health Study criteria. Using an inertial measurement unit, we measured parameters associated with the sole clearance and center of gravity shift. We then calculated the margin of stability in two directions. [Results] The gait analysis of both groups was reliable, as intraclass correlation coefficient values were comparable to the measurement accuracy of the inertial measurement unit achieved in a previous study of young participants. The results revealed that the sole clearance during the swing phase tended to be lower in frail than robust participants; moreover, the center of mass shift tended to be small and step width wide in frail participants, whereas the center of mass shift tended to be large in robust participants. [Conclusion] Our findings are expected to contribute to gait training in rehabilitation programs for older frail adults, the development of welfare equipment such as walking aids for frail elderly individuals, and the establishment of the reliability of inertial measurement unit use.

Key words: Frailty, Gait analysis, Margin of stability

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INTRODUCTION

With aging, people experience a decline in the ability to perform activities of daily living, including walking, excreting, eating, bathing, and dressing/undressing, with the most significant decline occurring in terms of walking[1]. Thus, in frail older adults, activities of daily living are particularly affected by the lower limb functions, which reflect the effects of physiological decline[2]. Therefore, we need to analyze the gait of this subset of the population and, based on this analysis, provide appropriate interventions to obtain stability in older adults' gait to maintain and improve their quality of daily life.

Gait analysis has been conducted on healthy adults and young adults wearing orthoses to simulate gait in older people[3, 4]; however, these simulations do not represent the actual walking ability of the frail elderly, as they do not account for the declines in neurophysiological functions found with aging, such as decreased nerve conduction velocity[5] and delayed maximum muscle exertion due to decreased firing rate in the central nervous system and neuromuscular junction[6]. Furthermore, the gait of walking on a treadmill in the laboratory may differ from that of ground-level walking in the middle-to-late phase of the gait cycle[7]. Additionally, walking on a treadmill does not differ significantly from ground-level walking when measured kinematically or electromyographically[8]. Therefore, the utility of treadmills in gait analysis is uncertain and dependent on

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the intended use. Analyzing the gait of the frail elderly in a laboratory setting is also challenging. Except in certain facilities, transporting elderly participants to the laboratory and ensuring their safety during gait analysis may be difficult. As a result, gait analysis[9, 10] of the elderly in the community has previously been conducted using an optical motion capture system in a facility in which the patients are hospitalized or staying[11]; nevertheless, it is challenging to walk long distances for analysis due to the number of cameras, location, and other installation factors.

Regarding gait stability and speed, Bruijn et al. evaluated 15 healthy young adults in their 20s using the Lyapunov index; they used an infrared camera for analysis and reported that the medial and lateral stability increased as gait speed increased[12]. Another study investigated gait stability in 10 healthy young participants using an optical motion capture system, with center of gravity shift along the X- (mediolateral) and Z-axes (vertical) as parameters: the study found that the mediolateral sway of the center of gravity decreased with increasing walking speed[13]. In 2013, Hak et al. conducted an infrared camera analysis of the margin of stability (MoS) in nine healthy young adults and reported that slow walking does not necessarily lead to walking stability and that increasing walking speed increases backward MoS and reduces the risk of falling[14]. A study using a video camera showed that ankle joint dorsiflexion did not change considerably during the swing phase in those who had experienced a fall[15]. This is because the difference between the maximum plantar flexion angle immediately after toe-off and the ankle joint angle at the end of the swing phase reduced due to a limited range of ankle joint motion or weakness of the plantar flexor muscles. In their review of studies on spinal curve measurement using radiography and other methods, Takai et al. observed that elderly people with a tendency toward round back are prone to fatigue and muscle pain in their lower limb muscles due to postural maintenance. This causes a secondary decline in lower limb muscle strength[16], which results in the inability of the plantar flexor muscles of the ankle joint to exert strength during toe-off. These factors ultimately lead to a gait pattern in which the lower limbs are lifted rather than kicked out using the plantar flexor muscles, resulting in a decrease in sole clearance. All of these studies used optical cameras, which are extremely useful for gathering marker location information; however, they have limited use in measurement environments, such as ground-level walking distance.

This preliminary study aimed to verify the usefulness of an inertial measurement unit (IMU), which provides greater freedom in the measurement environment than an optical camera, by extracting parameters that indicate differences in gait stability between frail and robust elderly and by calculating plantar clearance. The data were limited because the participants were frail elderly; nevertheless, we report new valuable findings in the analysis of the acquired data. We expect these findings to contribute to gait training in rehabilitation of the frail elderly, development of welfare equipment (such as walking aids) for frail elderly, and the reliability of using IMUs.

PARTICIPANTS AND METHODS

A total of 387 eligible patients visited the Integrated Healthy Aging Clinic (Locomo-Frailty Outpatient Clinic) at the National Center for Geriatrics and Gerontology in Obu City, Aichi Prefecture, Japan and provided consent to participate in the Locomotor Frail Sarcopenia Registry Study. We excluded 113 patients who were scheduled to undergo knee or hip joint surgery. Using the Japanese Cardiovascular Health Study criteria[17], we diagnosed 82 patients (75.0 ± 7.0 years) (mean ± standard deviation) as robust, 199 patients (76.4 ± 7.0 years) as prefrail, and 106 patients (80.0 ± 6.5 years) as frail. In order to obtain knowledge of the gait of frail elderly people using IMU as an initial analytical study, we first conducted a trial experiment by recruiting three frail elderly people and three healthy people. We included a total of six of these patients in the study: three males: R1, R2, and R3 (robust, aged 83.3 ± 2.1 years); and three females: F1, F2, and F3 (frail, aged 83.6 ± 0.6 years). The attributes of the participants are presented in Table 1.

This study was conducted in accordance with the tenets of the Declaration of Helsinki and with the approval of the ethics committee of our center (Locomo-Frailty Sarcopenia Registry Study Number 881). We obtained written informed consent from each participant.

Table 1. Participant attributes

Items	Robust (n=3)	Frail (n=3)
Gender	Male	Female
Age	83.3 ± 2.1	84.7 ± 2.1
Height (cm)	160.5 ± 4.1	150.5 ± 4.7
Body weight (kg)	57.1 ± 5.0	51.4 ± 6.9
Right leg strength (kgf)	32.3 ± 5.6	12.4 ± 4.9
Left leg strength (kgf)	28.10 ± 4.16	11.90 ± 4.83
Walking speed (m/s)	1.13 ± 0.12	0.64 ± 0.12
Stride (cm)	60.9 ± 6.5	35.9 ± 12.2
Step width (cm)	7.3 ± 1.8	11.5 ± 2.1

Data represented as mean ± standard deviation.

As shown in Fig. 1, fifteen accelerometers of IMU motion capture (Zero C Seven. Inc., Tokyo, Japan) were attached to the right side of the head, sternum, lower back (upper sacral vertebra), right and left upper arms, forearms, thighs, lower legs, feet dorsum, and upper scapula angles of each participant. The accelerometers were attached and fixed with Velcro belts and tapes. The sensor was attached to the foot with a sock using a magic belt; care was taken not to restrict the physiological foot movement. All participants removed their shoes and walked without aids. Each participant wore an IMU calibrated by walking several steps after standing at rest according to the device instructions. Then, the participants walked twice along the X-axis (front-back) at a comfortable walking speed on a 6.4-m-long walking path, including a 2-m-long auxiliary track in front of and behind a 2.4-m-long sheet-type foot pressure-ground gait analyzer (Walkway MW-1000, Anima, Tokyo, Japan). Next, they walked on a 30-m-long flat straight path at a comfortable walking speed. All participants diagnosed as frail used a T-cane when walking outdoors; therefore, a physical therapist followed the participants backward and laterally to prevent falls due to loss of balance while walking. The data obtained from the IMU were used to create stick pictures that included the sagittal plane, frontal plane, and top views, revealing the positions of the feet and the center of gravity. The time of the stance phase (single leg support) for each left and right lower limb was identified from the marker pattern on the stick picture. MoS was calculated from the relationship between the base of support (BoS) and extended center of mass (XCoM) using data at one time during the stance phase using equations (1) and (2) on the X- (antero-posterior direction) and Y-axes (mediolateral direction)[14, 18, 19]. BoS is the possible range of the center of pressure[20]; therefore, we defined the metatarsal head as the anterior edge and the midpoint between the toe and heel as the lateral edge. The midpoint between the left and right superior anterior iliac spine feature points was calculated as point A, and the sacral feature point projected at the same height as point A was calculated as point B. The midpoint between points A and B was defined as the center of mass (CoM).

$$\boldsymbol{XCoM}=\boldsymbol{CoM}+V_{\mathrm{CoM}}/\omega_0 \text{ ———— } (1)$$ [20–22]

V_{CoM}: ***CoM*** velocity [m/s],

$\omega_0=\sqrt{\frac{g}{l}}$: angular pendulum frequency, g: acceleration of gravity [9.81 m/s^2],

l: distance from the CoM to the foot [m]

$$\boldsymbol{MoS}=\boldsymbol{BoS}-\boldsymbol{XCoM} \text{ ———————— } (2)$$

BoS: Base of support position, CoM: Center of mass position.

MoS is the distance from the outer edge of BoS to XCoM. Therefore, a positive MoS value indicates that CoM is located within BoS and is stable. Conversely, a negative MoS value predicts that CoM is outside BoS and unstable. The larger the

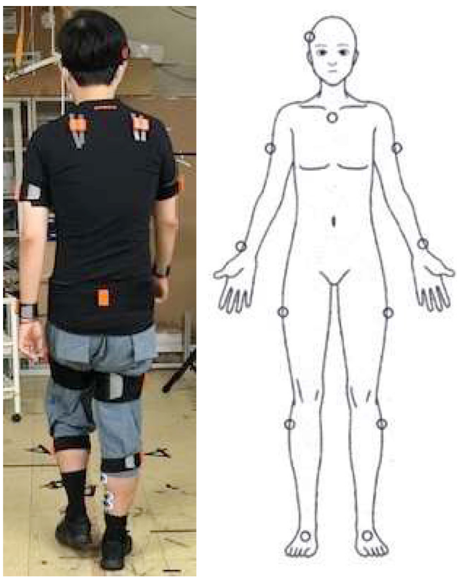

Fig. 1. Photo and scheme of sensors mounting position (○ marks means sensors in the scheme).
IMU sensors (3-axis gyro / 3-axis accelerometer/ 3-axis magnetometer, weight: 20 g) were attached to the right side of the head, sternum, lower back (upper sacral vertebra), right and left upper arms, forearms, thighs, lower legs, feet dorsum, and upper scapula angles of each participant.

absolute MoS value, the stronger the stability or instability[11]. Figure 2 illustrates the relationship between MoS and XCoM at the foot, and Fig. 3 illustrates the sole clearance.

The MoS and sole clearance of each participant were the mean values of step count data for 10 steps, 5 s after initiating the walk. In all cases, the left foot provided the non-dominant foot data. Lower limb muscle strength was calculated as the average of the isometric extensor muscle strength of both knee joints using a knee joint muscle strength-measuring device, which was developed by our center[23] using a strain gauge (zp-500N, IMADA Co., Ltd, Toyohashi, Aichi, Japan). ICC (1, 10) verified the reliability of the MoS_X, MoS_Y, and sole clearance data at 10 steps for each participant. The Shapiro–Wilk test confirmed the normality of MoS data, and the ICC was calculated. Statistical significance was set at $p<0.05$. We used the statistical software IBM SPSS Statistics for Windows Version 27 (IBM Corp., Armonk, NY, USA) for all statistical analyses.

RESULTS

Regarding MoS_x, as shown in Table 2, the F1, F2, and F3 for frail participants were 12.48 ± 0.66, 4.76 ± 1.68, and 4.78 ± 2.12 cm, respectively. The R1, R2, and R3 for robust participants were 6.80 ± 1.46, −4.75 ± 1.66, and −2.24 ± 2.06 cm, respectively. In terms of MoSy, frail F1 was −3.66 ± 0.77 cm, F2 was 4.54 ± 1.84 cm, and F3 was 6.27 ± 2.08 cm, while robust R1 was −0.17 ± 2.63 cm, R2 was −6.45 ± 6.59 cm, and R3 was −5.35 ± 2.56 cm. In terms of sole clearance, the F1, F2, and F3 for frail participants were 1.83 ± 0.63, 0.75 ± 0.50, and 0.61 ± 0.30 cm, respectively, while the R1, R2, and R3 for robust participants were 2.65 ± 0.54, 3.27 ± 0.42, and 1.80 ± 0.33 cm, respectively. R3 was 1.80 ± 0.33 cm.

Table 3 illustrates the ICCs of each left foot item at 10 steps for each of the three participants in the frail and robust groups. In frail participants, the average ICC was 0.95 (95% confidence interval [CI]): 0.777–0.999) for MoS_x, 0.99 (95% CI: 0.949–1.000) for MoS_Y, and 0.96 (95% CI: 0.831–0.999) for sole clearance. In robust participants, the ICC was 0.99 (95% CI: 0.963–1.000) for MoS_X, 0.83 (95% CI: 0.285–0.996) for MoS_Y, and 0.97 (95% CI: 0.850–0.999) for sole clearance.

DISCUSSION

In this study, the MoS_X values for frail participants tended to be higher than those for robust participants, indicating that the latter tended to shift their center of gravity forward beyond the basal plane of support while walking. In contrast, frail

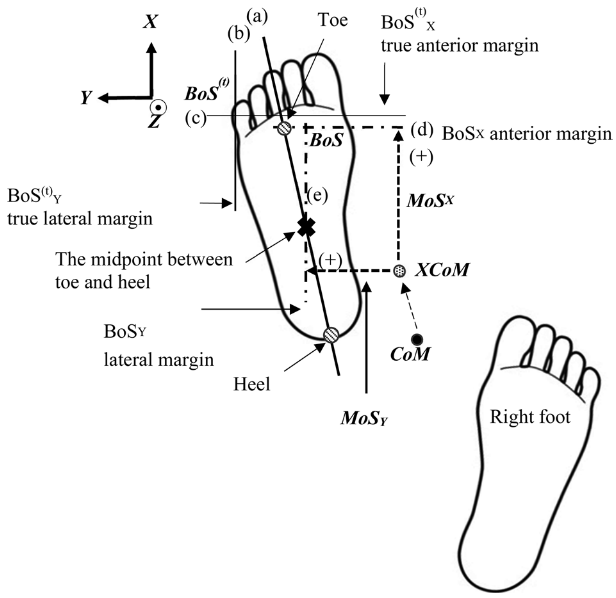

Fig. 2. Relationship between *XCoM* and *MoS* in the foot.
The X mark indicated the midpoint of the solid line (a) connecting the heel and toe. $BoS^{(t)}$ is a coordinate system with a true anterior margin of base of support along the ***X***-axis and a lateral margin along the ***Y***-axis. The solid line (b) was defined as the true lateral margin of $BoS^{(t)}_Y$, and the solid line (c) was defined as the true anterior margin of $BoS^{(t)}x$. The dashed dotted line (d) was defined as the anterior margin of BoS_X, and the dashed dotted line (e) was defined as the lateral margin of BoS_Y. MoS_Y (dashed arrow) represents the distance from the lateral margin of BoS_Y to ***XCoM***, and MoS_X (dashed arrow) represents the distance from the anterior margin of BoS_X to ***XCoM***.
MoS X-axis (MoS_X): Walking speed measured by the walkway was used for the X-axis speed.
MoS Y-axis (MoS_Y): The midpoint between the toe and heel is the support point. The approach velocity between the center of gravity and the support point was estimated to be the moving velocity in the Y-axis direction.
XCoM: extended center of mass; ***MoS***: margin of stability; BoS: base of support; CoM: center of mass.

participants tended to take small steps in the motion direction, placing their estimated center of gravity more within the basal plane of support; we assume that this reduced their walking speed.

Stride length is involved in slow walking speed. A study that used optical motion capture and floor reaction force reported meter ankle plantar flexor and hip extensor strengths as independent predicting factors for stride length[24]. The National

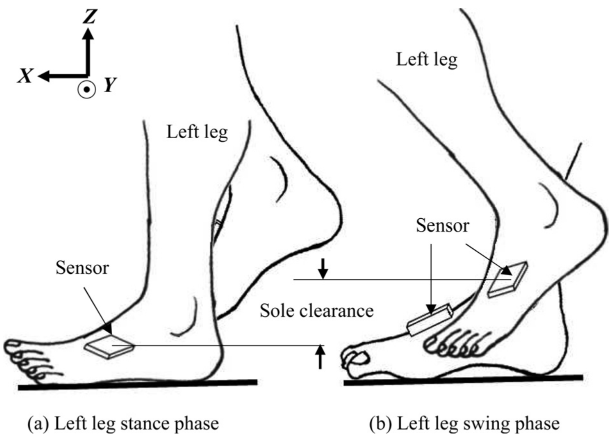

Fig. 3. Sole clearance.
(a) the left leg stance phase, (b) the left leg swing phase.
The difference between the ***Z***-coordinate of the lowest point of the sensor in the stance phase of the left leg and the highest point of the sensor in the swing phase of the left leg was defined as the sole clearance.
Sole clearance: The Z-coordinate of the left swing leg marker was compared with the Z-coordinate of the left stance leg marker, and defined as sole clearance. Each Z-coordinate marker was corrected so that the minimum value on the Z-axis of the model was 0 to prevent the Z-axis coordinates from being negative.

Table 2. Results of MoS and sole clearance

	Robust		
Contents	R1	R2	R3
MoS X-axis (cm)	6.80 ± 1.46	−4.75 ± 1.66	−2.24 ± 2.06
MoS Y-axis (cm)	−0.59 ± 1.62	−0.97 ± 1.24	−5.45 ± 2.19
Sole clearance (cm)	2.65 ± 0.54	3.27 ± 0.42	1.80 ± 0.33
	Frail		
Contents	F1	F2	F3
MoS X-axis (cm)	12.48 ± 0.66	4.76 ± 1.68	4.78 ± 2.12
MoS Y-axis (cm)	−3.66 ± 0.77	4.54 ± 1.84	6.27 ± 2.08
Sole clearance (cm)	1.83 ± 0.63	0.75 ± 0.50	0.61 ± 0.30

Data represented as mean ± standard deviation.
MoS: margin of stability.

Table 3. Intra-class correlation coefficient of each measurement item for the frail and robust

		Measurement value	95% confidence intervals		
			ICC	LL	UL
Frail	MoS_X***	Average	0.948	0.777	0.999
	MoS_Y***	Average	0.988	0.949	1
	Sole clearance***	Average	0.96	0.831	0.999
Robust	MoS_X***	Average	0.991	0.963	1
	MoS_Y**	Average	0.831	0.285	0.996
	Sole clearance***	Average	0.965	0.85	0.999

***p<0.001, **p<0.01
ICC: intraclass correlation coefficient; LL: lower limitation; UL: upper limitation.

Institute for Longevity Sciences-Longitudinal Study of Aging (NILS-LSA) data found that robust females in their 80s had a stride length of 56.3 cm, gait speed of 108.6 cm/s, left knee extensor strength of 17.9 kgf, and right knee extensor strength of 19.6 kgf[25]. The study compared these data with those of frail participants, also in their 80s. In our study, frail participants had a smaller stride length and lower knee extension muscle strength than frail participants in the NILS-LSA study; both these parameters may have caused a decrease in walking speed of the participants. Frail participants tended to have higher MoS_Y than robust participants. Widening the step width can increase MoS_Y in the mediolateral direction. In a comparative study between young and older participants, Oyake et al. revealed that the left-right shift of the center of gravity and the step width were significantly larger in older participants than in young participants[26]. In this study, frail participants tended to have a larger step width than robust participants (Table 1). This finding suggests that there is a difference in step width, not only between the young and the older, but also between the frail older and robust older participants; frail participants try to maintain their balance with a wider support surface. Therefore, the frail avoided a center of gravity shift to the BoS limit and walked stably with a wide step width so that the XCoM was close to the CoM in the basal plane of support. In addition, frail participants with slower walking speeds had larger values of MoS_X and MoS_Y than robust participants, indicating the characteristics of frail walking from the viewpoint of stability analysis using MoS.

The robust group had higher sole clearance values than the frail group. Kobayashi et al. reported that toe height in the first half of the swing phase was low in participants who had experienced a fall[4]; however, in this study, frail participants had lower knee joint extensor strength than robust participants. Therefore, there was less lifting of the lower limb during the swing phase; thus, the risk of tripping over low-height obstacles may be higher in the frail participants than in robust participants. Sole clearance is increased to ensure safety against toe dragging in older adults[27]; therefore, interpretation should be cautiously made when analyzing sole clearance in older adults. McAndrew Young and Dingwell reported that, in healthy young participants, walking with a wider step width than normal significantly decreased MoS in the anterior-posterior direction and significantly increased MoS in the mediolateral direction[28]. The negative correlation between MoS_X and MoS_Y in frail participants in this study indicates the phenomenon of walking with a wider step width.

Bakhshi et al. compared the accuracy of IMU motion capture with optical motion capture in young people[29]. They compared the angles of the knee joint using four tasks: seated lower leg swing, standing hip and knee flexion of one leg, crouching and standing, and a combination of walking and squatting with the angles obtained from optical motion capture. The results revealed a high correlation (r) of >0.94 for all four tasks. The accuracy obtained for the frail older adults in this study is presented in Table 3, and the mean ICC values were as high as the accuracy obtained for younger people by Bakhshi et al. Therefore, the IMU is a useful tool for analyzing the gait of frail older adults.

The first limitation of this study is the position and fixation method of the IMU sensor attached to the foot. In this study, the IMU sensor was generally installed on the foot. As illustrated in Fig. 1, the true anterior margin of BoS (Fig. 1c) is anteriorly located along the X-axis from the sensor attachment point, which may have affected the MoS values for the anterior direction. In addition, the true lateral margin of BoS (Fig. 1b) is outward along the Y-axis from the sensor attachment point, which may have affected the MoS values for the lateral direction. Furthermore, the mounting method of the sensor may not have been strong enough to prevent the sensor from shaking within the magic belt. Second, ethical regulations did not permit video recording; therefore, it was impossible to refer to each participant's gait cycle and acceleration data on video. Lastly, the low number of cases prevented statistically adequate group comparisons, and coincidentally gender bias occurred in the robust and frail participants' data. If the number of cases were increased, analyses could be conducted without gender bias in robust and frail participants in the future, and if measures were taken that considered these research limitations, applying IMU motion capture to gait analysis could be useful.

As a future research project, in this study, we found a tendency for differences in center of gravity deviation using Mos between normal and prefrail. Therefore, we would like to increase the number of cases to obtain the cutoff value of the center of gravity deviation using Mos in prefrail compared to normal. Also, in order to verify the usefulness of using IMU, we would like to conduct a study to compare gait analysis by IMU using Mos with analysis by optical camera.

In conclusion, this study used IMU motion capture to analyze the gait of three frail older adult females and three robust older males. Two types of MoS were calculated: MoS in the X-axis direction, the direction of movement, and MoS in the Y-axis direction, representing the medial and lateral directions. We also calculated values for sole clearance for each participant. Our findings revealed that the MoS in the X- and Y-axes tended to be higher in frail participants than in robust participants. In addition, the sole clearance tended to be greater in robust participants than that in frail participants. These results suggest that participants in the frail group had a more stable gait than those in the robust group, and they achieved this by moving the XCoM in the basal plane of support and by widening step width. Thus, from a stability analysis viewpoint using MoS, the characteristics of frail gait were demonstrated. Frail participants may be more prone to stumble than the robust participants due to their low sole clearance. The high ICC value calculated in the gait analysis suggests that IMU has a high reliability when analyzing frail gait.

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Conflict of interest

The authors declare no conflict of interest.

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