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## RESEARCH ARTICLE

# The Effects of Ship's Roll Motion on the Center of Mass and Margin of Stability During Walking: A Simulation Study

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**ABSTRACT** Walking strategies in an unstable environment like a ship differ from walking on stable ground. Extreme ship motions may endanger the safety of the crews. Notably, a loss of balance on board can lead to an injury or an accident of falling off a ship. Keeping one's balance on board a ship is strongly influenced by the ship's motion. Therefore, the objective of this study is to determine how walking on a ship differs from walking in a stable environment and explore the effects of the ship's roll motion on balance control and stability while walking in sea environments. We hypothesized that step time variability, center of mass (COM), and margin of stability (MOS) would significantly differ between stable and unstable walking conditions. We also hypothesized that there would be an effect of rolling cycles and angles on increasing step time variability, COM excursion, and MOS variability. We recruited 30 healthy individuals between 21 and 39 years old for this study. Participants walked for two minutes at their self-selected speeds during the study with and without rolling on a computer-assisted rehabilitation environment (CAREN) system. The CAREN system was used to simulate the parametric roll motion of ships up to 20 degrees. This study quantified step time variability, peak COM excursion, and MOS variability in different rolling conditions. We found a significant difference in step time variability ( $p < 0.001$ ), lateral peak COM excursion ( $p < 0.001$ ), and MOS variability ( $p < 0.001$ ) between walking on land and walking at sea.

**INDEX TERMS** CAREN, center of mass, lateral balance, margin of stability, ship's roll motion, walking.

## I. INTRODUCTION

Daily walking is a good indication of health and one of the most basic movements in life. The characteristics of human walking vary from one individual to another, and walking strategies can be modified according to the walking environment [1]. In particular, walking on a moving vessel will be considerably different from walking on land. A ship's motion plays an important role in affecting walking ability, thereby

directly limiting the human gait [1], [2]. Several studies have examined walking on a ship [3], [4], [5], [6], but there is still a significant lack of research analyzing gait characteristics in unstable moving environments. Thus, we are investigating how walking on a ship differs from walking on land.

Extreme fluctuations of the ship at sea may threaten not only the ship itself but also the safety of the crew. Notably, a loss of balance on board can lead to a severe injury as the ship is made of steel. Balancing the body at sea is strongly influenced by the motion of ships, such as rolling and pitching. To reduce the rate of man overboard accidents, safety

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work regulations on ships are necessary for occurrences of ship agitation. However, there are currently no clear work safety rules that regulate work on a ship based on the degree of motion of ships. Furthermore, recent papers have investigated the ship's roll motion relative to equipment of ship [7], [8], but there is a lack of human walking studies. Therefore, we would like to investigate how the ability to control balance changes depending on the degree of ship movement to help establish working safety rules for ships in bad weather. In general, the ship's motion is greater in a roll than in pitch because the length of a ship is longer than the width [5]. Consequently, we focused on the ship's roll motion in this study.

Walking stability is influenced by the motion of the center of mass (COM) [9], [10]. In many studies, gait stability has been examined using the COM motion of the whole body in relation to the center of pressure (COP) of the supporting foot [9], [11], [12]. Balance during walking can be achieved by continuously adjusting the location of the body's COM with regard to the base of support (BOS) [13]. However, it has been suggested that the velocity of COM should also be considered because the previous approach is insufficient in dynamic situations [14]. To overcome this limitation, the margin of stability (MOS), a measure of dynamic stability during walking, was proposed by introducing the concept of the extrapolated COM (XcoM) [15]. In this study, we calculated the COM and the MOS in lateral directions to examine the stability of walking in sea environments.

The purpose of this study is to explore the characteristics of walking on a ship by determining the effects of the ship's roll motion on the balance control and stability while walking in sea environments. Experiments on a ship at sea are subject to a number of restrictions, including unpredictable weather (e.g., sea, wave, wind, swell, etc.), heavy ship motion, and the possibility of an accident. To address this limitation, we used a computer-assisted rehabilitation environment (CAREN) system that can simulate a consistent ship's motion by supporting 6 degrees of freedom (DOF) motion. Various ship's roll motions were simulated up to 20 degrees of rolling with the CAREN system. To achieve our objective, we quantified step time variability, COM excursion, and MOS variability. We hypothesized that there would be significant differences in step time variability, COM excursion, and MOS variability between the different conditions with and without rolling motions. We also hypothesized that there would be an effect of rolling cycles and angles on increasing step time variability, COM excursion, and MOS variability.

To our best knowledge, this paper is the first attempt to explore human walking characteristics in unstable sea environments with different roll motions. While weather and wind play an important role, it is currently tough to simulate strong sea wind in indoor facilities, and only the effects of roll motion were investigated in this study by excluding other external factors. This study can help us better understand the characteristics of walking stability in ship's roll motions, and we can propose a specific working safety regulation for seafarers as well as this can be used to prevent crew's

injuries or accidents on the ship at sea by assessing gait instability.

## II. METHODS

### A. PARTICIPANTS

Thirty healthy young adults (20 males and 10 females) participated in this study. The characteristics of the participants are shown in Table 1. Participants were excluded if they had 1) major lower extremity injury or surgery; 2) known cardiovascular conditions that make it unsafe for them to exercise; 3) a history of dizziness due to vestibular disorders such as Meniere's disease and vertigo; 4) any difficulty in walking in unstable moving environments. All subjects signed an informed consent form before data collection. This study was approved by the Institutional Review Board at the University of Nebraska Medical Center (IRB 141-21-EP).

TABLE 1. Participants' characteristics.

Characteristics	Mean $\pm$ SD
Age (years)	30.3 $\pm$ 6.1
Height (cm)	173.0 $\pm$ 9.4
Weight (kg)	71.9 $\pm$ 14.5
BMI (kg/m <sup>2</sup> )	23.8 $\pm$ 3.4

SD = standard deviation, BMI = body mass index.

### B. EQUIPMENT

A 3-dimensional motion capture system (Vicon Motion System Ltd., Oxford, UK) with ten cameras was used to record marker trajectories at 100 Hz. A total of 37 reflective markers were placed on anatomical landmarks according to the Plug-in Gait full-body model [16], including 4 markers on the head, 5 on the torso, 12 on the upper limb, 4 on the pelvis, and 12 on the lower limb.

We placed 7 wireless inertial measurement unit (IMU) sensors (Xsens, Enschede, Netherlands) to obtain 3-axial accelerations from the pelvis and each foot/shank/thigh segment. Fig. 1 shows the placement of reflective markers and IMU sensors attached to each subject's body. The CAREN system (Motek, Amsterdam, Netherlands) was also used to simulate the roll motion of a ship for up to 20 degrees of rolling.

### C. EXPERIMENTAL PROTOCOL

All participants walked on a split-belt treadmill for 2 minutes at a self-selected comfortable pace. Each participant completed nine 2-minute walking trials in the CAREN system for each of the following conditions: no rolling (NR), 5-, 10-, 15-, and 20-degrees of rolling with slow (12s) and fast (6s) rolling cycles (i.e., each rolling condition was abbreviated as SR5, SR10, SR15, SR20, FR5, FR10, FR15, and FR20). Since several existing studies have used different incline degrees like 5, 10, 15, and 20 to examine the evacuation walking time in emergency situation at sea [17], [15], [19], we selected the same rolling angles in our experiments. For the slow and



FIGURE 1. Placement of reflective markers and IMU sensors.

fast-rolling cycles, we followed a typical rolling cycle for a passenger ship of 12 seconds and a general cargo ship of 6 seconds, respectively [20].

Participants were placed in a safety harness secured to prevent accidental falls on the moving platform. Following the walking with no rolling, eight different walking trials in rolling motions were performed in random order to avoid learning effects. In addition, participants were asked to complete a self-report questionnaire using a Likert scale. The Likert scale questionnaire has been used most frequently to investigate individual differences, including motivation, anxiety, and self-esteem, since it is a psychometric scale with multiple categories on which respondents can express their opinions, attitudes, or feelings regarding a particular issue [21]. We used an 11-point Likert scale to determine the balance difficulty of each trial from 0 to 10 (from “very easy” to “very difficult”).

D. DATA PROCESSING

1) STEP TIME VARIABILITY

A step event was recognized by detecting heel-strike using the peak detection algorithm with data obtained by accelerometers [22], [23]. Step time was defined as the time from heel strike to heel strike. Step time variability was calculated using the standard deviation of step time. Since step time variability is one of the most important indicators of impaired mobility in gait studies [24], [25], we explored the effect of the ship’s motion on the increase in step time variability to identify a specific rolling angle that can cause mobility impairment in sea environments.

2) COM EXCURSION

A total of 37 markers were reconstructed and labeled using Vicon Nexus software (Oxford Metric, Oxford, UK). For each subject, a 15-segment model has been created to quantify COM motion. The position of COM was extracted by Nexus software. Since it is crucial to control the COM excursion to recover the balance [26], peak COM excursion in the lateral direction was calculated for data analysis. Many researchers

have examined the changes in the control of COM in various conditions [26], [27], [18], [29], [30], but we focused on the changes in the COM excursion with a ship’s roll motion simulations.

3) MOS VARIABILITY

MOS is defined as the distance between the XcoM and the BOS. The MOS is well depicted in Fig. 2. To calculate the lateral MOS, we used the following equation introduced by [15]:

$$MOS = X_{coM} - BOS \tag{1}$$

where BOS is the lateral boundary of the base of support (the lateral malleolus marker on each ankle at heel strike), and XcoM is calculated as:

$$X_{coM} = COM + \frac{vCOM}{w_0} \tag{2}$$

where COM is the lateral position of COM at heel strike, vCOM is the COM velocity that is computed as the derivative of the COM position at heel strike, and w<sub>0</sub> is defined as:

$$w_0 = \sqrt{\frac{g}{l}} \tag{3}$$

where g is the gravitational constant (9.81 m/s<sup>2</sup>) and l is the pendulum length, which is defined as the mean distance between the ankle marker and the COM in this study. The MOS will be considered stable if the XcoM is placed within the BOS. In contrast, if the XcoM is positioned outside of the BOS, the MOS will be considered unstable [13]. The MOS variability was calculated as the standard deviation of MOS across all trials.

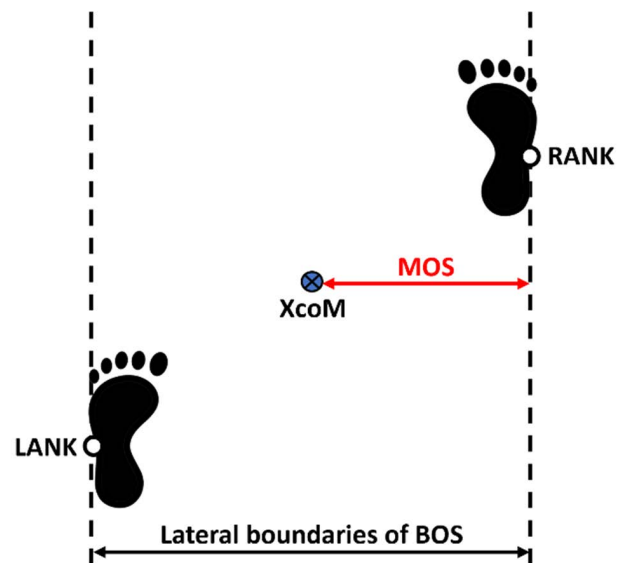


FIGURE 2. Lateral MOS was defined as the distance between the lateral boundary of the BOS and the XcoM. The lateral boundary of the BOS was defined by the ankle marker of the lead foot (RANK and LANK for the right and left foot, respectively).

**TABLE 2.** The mean of self-reported balance difficulty scores for each condition (standard deviations are shown in brackets).

NR	SR5	FR5	SR10	FR10	SR15	FR15	SR20	FR20
1.17 (0.46)	2.00 (0.91)	2.40 (0.89)	2.97 (0.96)	3.77 (1.22)	4.43 (1.28)	4.87 (1.38)	6.03 (1.52)	6.37 (1.54)

**TABLE 3.** Results of ANOVA test for self-reported balance difficulty scores.

Source	Sum of Squares	Degrees of freedom	Mean Square	F-value	p-value
Conditions	778.20	8	97.275	70.04	< 0.001 *
Error	362.47	261	1.389		
Total	1140.67	269			

\*  $p < 0.05$

**E. STATISTICAL ANALYSIS**

One-way analyses of variance (ANOVAs) with a Tukey post-hoc test were used to see the differences between a self-reported balance difficulty scale, step time variability, peak lateral COM excursion, and lateral MOS variability in different rolling conditions compared with no rolling condition. A two-way repeated-measures multivariate ANOVA (MANOVA) was performed to assess if the two rolling cycles and four rolling angles had significantly different effects on the combination of the three dependent variables (step time variability, peak COM excursion, and MOS variability). MANOVA assumptions were checked beforehand, and Wilks' lambda was selected as the test statistic of the repeated measures MANOVA. The separate univariate two-way (2 rolling cycles X 4 rolling angles) repeated measures ANOVAs were used to determine the effects of rolling angles and rolling cycles as well as their interactions with the step time variability, peak COM excursion, and MOS variability, respectively. Post-hoc analyses with a Bonferroni method were performed to determine differences between the different experimental rolling conditions. Significance was determined at an alpha level of 0.05. All statistical analyses were performed with MATLAB version R2020a (Mathworks Inc., Natick, MA).

**III. RESULTS**

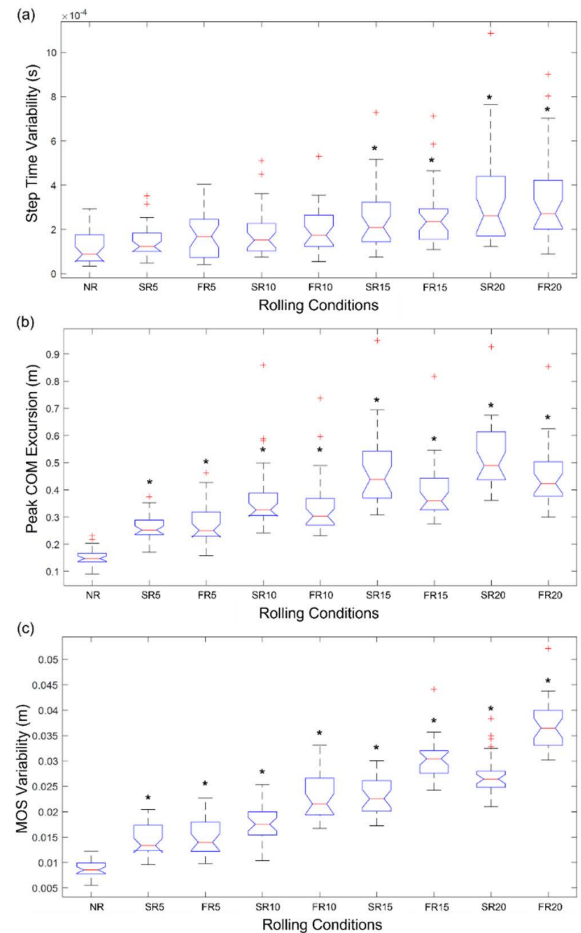
**A. SELF-REPORTED BALANCE DIFFICULTY**

Mean scores of self-reported balance difficulty measures for each condition are shown in Table 2. There were statistically significant differences between rolling conditions (Table 3,  $F = 70.04, p < 0.001$ ) in balance difficulty scores. Multiple comparisons were performed to determine the differences between conditions using a Tukey method. The results of post-hoc tests are summarized in Table 5. There were no differences between NR and SR5 ( $p = 0.134$ ), SR5 and FR5 ( $p = 0.927$ ), FR5 and SR10 ( $p = 0.640$ ), SR10 and FR10 ( $p = 0.174$ ), FR10 and SR15 ( $p = 0.411$ ), SR15 and FR15 ( $p = 0.889$ ), and SR20 and FR20 ( $p = 0.975$ ). However, there were statistically significant differences in all other conditions (detailed in supplemental Table S1,  $p < 0.05$ ).

**TABLE 4.** Results of MANOVA test for all dependent variables with Wilks' Lambda.

Effect	Value	F-value	d.f.1	d.f.2	p-value
Cycle	0.499	115.7	2	231	< 0.001*
Angle	0.252	76.246	6	462	< 0.001*
Cycle * Angle	0.717	13.934	6	462	< 0.001*

\*  $p < 0.05$ , d.f. = degrees of freedom



**FIGURE 3.** Box plots for the mean differences between the different rolling conditions in (a) step time variability, (b) peak lateral COM excursion, and (c) lateral MOS variability. \* symbol indicates significant ( $p < 0.05$ ) differences from NR. Compared to the NR condition, Step time variabilities were significantly increased in SR15, FR15, SR20, and FR20 conditions, Peak COM excursions and MOS variabilities were significantly increased in a lateral direction for all rolling conditions.

**B. RESULTS OF REPEATED MEASURES MANOVA**

The two-way repeated measures MANOVA was used to examine if step time variability, peak COM excursion, and MOS variability differed according to rolling cycle or rolling angle. The MANOVA revealed that there were significant main effects of both rolling cycle (Table 4,  $F = 115.7, p < 0.001$ ) and rolling angle (Table 4,  $F = 76.246, p < 0.001$ ) as well as there was a significant interaction between rolling cycle and rolling angle (Table 4,  $F = 13.934, p < 0.001$ ) for step time variability, peak COM excursion, and MOS variability.

**TABLE 5.** Results of two-way repeated-measures ANOVAs for step time variability, COM Excursion, and MOS Variability (values represents as mean ± standard deviation).

Variable	Slow Rolling Cycle					Fast Rolling Cycle				p-value		
	NR	SR5	SR10	SR15	SR20	FR5	FR10	FR15	FR20	Main Effect (Cycle)	Main Effect (Angle)	Interaction Effect (Cycle x Angle)
Step Time Variability (s)	0.0001 ± 0.0001	0.0001 ± 0.0001	0.0002 ± 0.0001	0.0002 ± 0.0002	0.0003 ± 0.0002	0.0002 ± 0.0001	0.0002 ± 0.0001	0.0003 ± 0.0001	0.0003 ± 0.0002	0.682	<0.001*	0.810
	COM Excursion (m)	0.153 ± 0.032	0.262 ± 0.046	0.372 ± 0.124	0.468 ± 0.142	0.529 ± 0.122	0.270 ± 0.069	0.340 ± 0.107	0.394 ± 0.105			
MOS Variability (m)	0.009 ± 0.002	0.014 ± 0.003	0.018 ± 0.004	0.023 ± 0.004	0.027 ± 0.004	0.015 ± 0.004	0.023 ± 0.004	0.030 ± 0.004	0.037 ± 0.005	<0.001*	<0.001*	<0.001*

\*  $p < 0.05$

**C. ANALYSIS OF STEP TIME VARIABILITY**

Step time variabilities in SR15, FR15, SR20, and FR20 conditions (Fig. 3a, supplemental Table S2,  $p = 0.009$ ,  $0.003$ ,  $<0.001$ , and  $<0.001$ , respectively) were significantly increased compared to the NR condition. There was no significant main effect of the rolling cycle (Table 5, supplemental Table S4,  $p = 0.682$ ) and no significant interaction effect between the rolling cycle and the rolling angle (Table 5,  $p = 0.810$ ) on step time variability. However, there was a significant main effect of rolling angles on step time variability (Table 5,  $p < 0.001$ ). In both fast and slow rolling cycles, the post-hoc analysis indicated that there were significant differences in step time variability between most of the rolling angles other than between 5 and 10 degrees (supplemental Table S3). To check only the effect of the rolling angles regardless of the rolling cycles, we also compared the step time variability by combining different rolling cycle data for the same rolling angle (i.e., the data of 5 degrees = SR5 + FR5). Similarly, step time variabilities in 15 and 20 degrees of rolling conditions were significantly greater than in the NR condition (Fig. 4a). We also found that there were significant differences in step time variability in most of the rolling angles except for between 5 and 10 degrees and between 10 and 15 degrees (Fig. 4a).

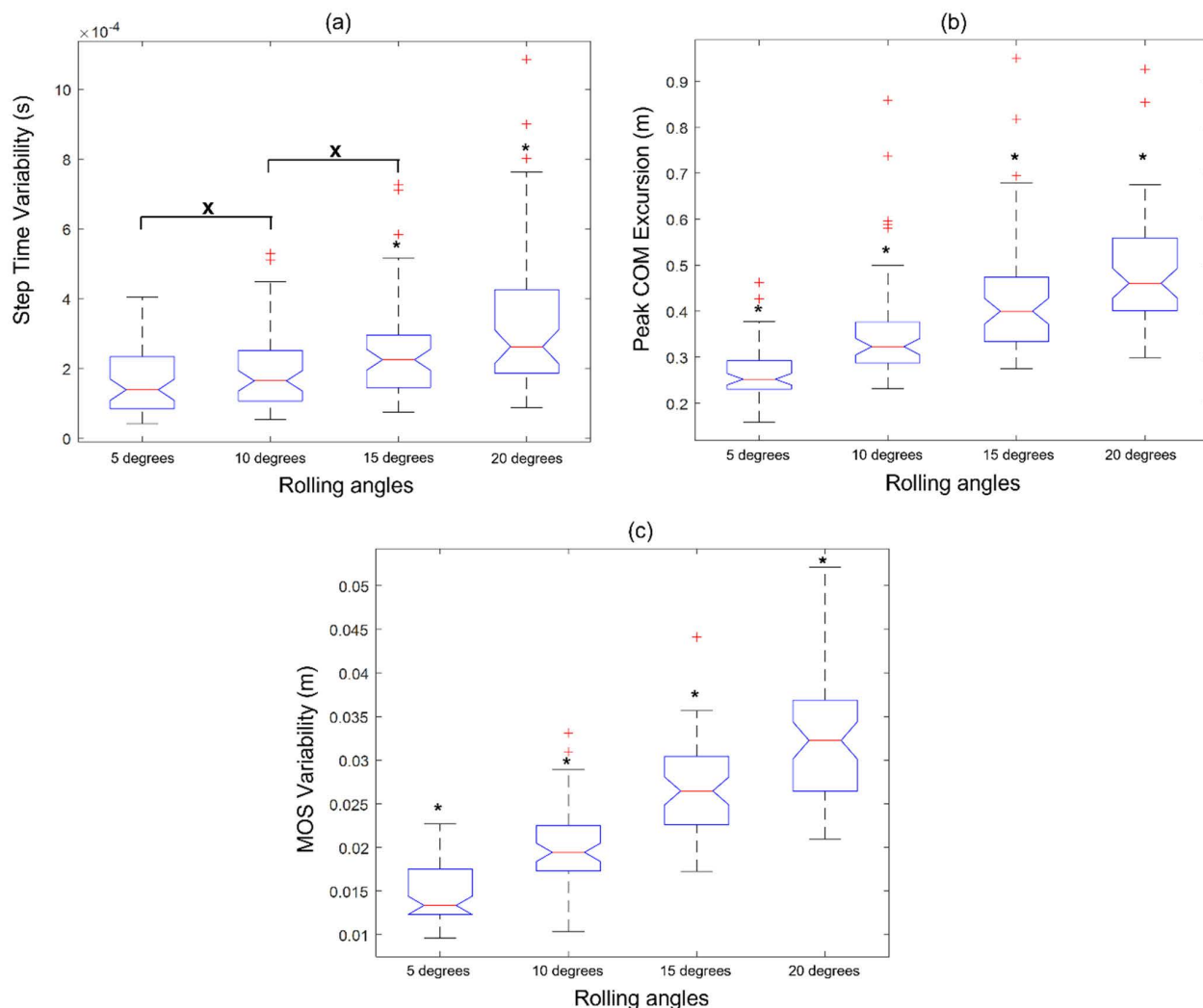
**D. ANALYSIS OF COM EXCURSION**

Peak COM excursions in the lateral direction across all rolling conditions (Fig. 3b, supplemental Table S5,  $p < 0.001$ ) were significantly increased compared to the NR condition. There

was no significant main effect of the rolling cycle (Table 5,  $p = 0.067$ ) on the peak COM excursion. However, there was a significant main effect of the rolling angle on peak COM excursion (Table 5,  $p < 0.001$ ). Post-hoc analysis revealed that there were significant differences in the peak COM excursion between the different rolling angles (supplemental Table S6). Based on the results of the effect of the rolling angle only, we also observed that there were significant differences in peak COM excursion at different rolling angles (Fig. 4b). A significant interaction effect between the rolling cycle and the rolling angle was found in the lateral peak COM excursion (Table 5).

**E. ANALYSIS OF MOS VARIABILITY**

The MOS variabilities in a lateral direction for all rolling conditions (Fig. 3c, supplemental Table S8,  $p < 0.001$ ) were significantly increased compared to the NR condition. There was a significant main effect of the rolling cycle (Table 5,  $p < 0.001$ ) in the MOS variability. Post-hoc analysis showed that the MOS variability during the fast-rolling cycle was higher than during the slow-rolling cycle in most rolling angles other than in 5 degrees of rolling motion (supplemental Table S10). A significant main effect of the rolling angle on the MOS variability was found with all rolling conditions (Table 5, supplemental Table S9,  $p < 0.001$ ). There was a significant interaction effect between the rolling cycle and the rolling angle in the MOS variability. Additionally, we noted that the MOS variability at the different rolling angles, irrespective



**FIGURE 4.** Effects of rolling angles on (a) step time variability, (b) peak lateral COM excursion, and (c) lateral MOS variability. '\*' symbol indicates significant ( $p < 0.05$ ) differences from NR. 'x' symbol represents no significant differences between conditions. Step time variabilities were significantly greater in 15 and 20 degrees of rolling conditions than in the NR condition. Peak COM excursion and MOS variability at the different rolling angles were significantly different from the NR condition.

of rolling cycles, was significantly different from the NR condition (Fig. 4c).

#### IV. DISCUSSION

This study aimed to investigate how walking in an unstable ship environment differs from walking on stable land and how the ship's roll motion affects balance control and stability while walking in sea environments. To our knowledge, this is the first study to examine walking characteristics in unstable sea environments by simulating different levels of rolling motion. As expected, the rolling motion of ships affected the gait variability, the control of balance, and dynamic stability. We hypothesized that there would be significant differences in step time variability, COM excursion, and MOS variability between with and without rolling motions, and these variables would be affected by rolling cycles and angles. The results of the study agree with our first hypothesis because step time variability, peak COM excursion, and MOS variability in

the simulated sea conditions were significantly greater than with no rolling motions. We partially confirmed our second hypothesis since rolling angles affected increasing step time variability, peak COM excursion, and MOS variability while rolling cycles influenced only the MOS variability. Moreover, based on the MANOVA results, we also found that the rolling cycle, rolling angle, and their interaction were significant for all three dependent variables, which shows that there is interdependency among the dependent variables: step time variability, peak COM excursion, and MOS variability.

We found that the ship's rolling motion increased the step time variability (Fig. 3a), and this is thought to have rapidly changed the walking steps to balance in an unstable environment. We also found that the step time variability was significantly increased at a rolling angle of 15 degrees or higher compared to no rolling condition (Fig. 3a, Fig. 4a). In addition, many participants responded that the balance difficulty increased rapidly at 20 degrees in their self-reported

questionnaires (Table 2). Based on these two results, this study could propose a crew's work safety rule that limits or requires attention to deck work in at least 15 degrees or higher rolling environments.

Peak COM excursion was increased substantially during walking in rolling conditions (Fig. 3b, Fig. 4b). We found that the higher degree of rolling increased the peak COM excursion in the lateral direction, which means the COM moved more laterally to balance in higher rolling motions. Furthermore, there was a significant increase in MOS variability under rolling conditions (Fig. 3c, Fig. 4c), indicating a more significant stability challenge. This result is similar to findings from a study by [31]. The findings of increased peak COM excursion and MOS variability may predict an increased risk of falls by increasing the gait variability. Thus, peak COM excursion and MOS variability measures can be good indicators of instability at sea. This study could help prevent falls from ships at sea by assessing fall risk through these results.

There are several limitations. The first limitation is that the subjects are relatively young and healthy individuals, so it is hard to learn walking characteristics at various ages or health statuses and generalize our results to different populations. Typically, cruise ship passengers are dominated by middle-aged and older adults with relatively poor balancing ability. Thus, it is necessary to conduct experiments with the elderly in the future. However, in a general merchant ship, since relatively young trainees or new sailors are not familiar with the ship's environment, it will not be easy to control the balance on the ship compared to skilled sailors. Therefore, our findings are sufficient to understand the characteristics of how these new sailors control balance on ships. The second limitation is that only rolling motion was applied in the experiment. The ship performs six degrees of freedom in the real sea environment, including three linear movements: heave, surge, and sway, and three rotational movements: roll, pitch, and yaw. However, since the ship's length is longer than the width, the movement that can be felt the most in the actual ship is the rolling motion. Since this study is the starting point for the study of walking in the sea environment, the experiment was conducted focusing on rolling, the main movement of ships. In addition to ship motions, weather conditions such as wind, sea height, wave, and swell could play a major role in the assessing instability in real situation. Thus, future research needs to mix more realistic ship movements and weather conditions. The third limitation is that the human factors were not considered in this study. The participants' height may impact peak COM excursion because the step width or length may be lengthened across the higher heights, and the change in the COM may increase accordingly. Additionally, a previous study found that the lateral MOS is affected by age and BMI [32]. Men and women may differ in their levels of dynamic stability during walking [33], which could be an interesting topic to investigate since the difference in balance control ability between men and women could affect walking differently in moving environments.

Thus, these human factors, such as age, sex, height, and BMI, should be taken into account in future studies. Lastly, the rolling angle was limited to 20 degrees in the experimental setting. In fact, rolling of more than 20 degrees occurs in bad weather at sea, which significantly hinders the crew's safety by making it difficult to control the balance. In this study, it was inevitable to set the rolling angle up to 20 degrees due to technical problems with the CAREN system, which supports up to 20 degrees. However, this study found walking characteristics that could sufficiently endanger safety even at 15 or 20 degrees. Additional studies would need to validate our experimental results in the actual ship environment at sea.

## V. CONCLUSION

In conclusion, this study examined the effects of a ship's rolling motion on the changes in human walking characteristics such as step time variability, COM excursion, and MOS variability in the sea environment. Study results indicate that different rolling angles have an impact on increasing step time variability, peak COM excursion, and MOS variability, but the rolling cycles influence MOS variability only. Peak COM excursion and MOS variability can effectively assess dynamic stability during walking on a ship at sea. Thus, this study could propose a crew's work safety rule that limits or requires attention to deck work on a ship and help prevent injuries on the ship at sea by assessing gait instability. Further studies are needed to confirm our results in a real ship at sea and to investigate the possibility of the use of our measures to prevent falling overboard.

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