Experimental study on individual walking speed during emergency evacuation with the influence of ship motion

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ABSTRACT

Ship motion is an important influencing factor in passenger ship evacuation that affects the entire evacuation process by reducing individual walking speed. This study used Dalian Maritime University's training ship to conduct human walking experiments to study the influence of ship motion onNormal and fast walking speeds. It was found that during the berthing period, the individual Normal walking speed was 1.28–1.68 m/s, and the fast walking speed was 1.50–2.14 m/s. During the voyage, the ship's rolling motion reduced the Normal walking speed by 3.8%–10.3% and the fast walking speed by 3.7–14.0%. Due to the influence of ship rolling, the higher the deck and the farther away the rolling centre is, the smaller the athwartship and fore-aft walking speeds. Athwartship walking was slightly faster than fore-aft walking. In the Normal walking mode, the athwartship walking speed was 1.6%–3.7% faster than fore-aft walking, and in the fast walking mode, the athwartship walking speed was 0.8%–4.9% faster than fore-aft walking. During the berthing period, the average speed of the younger group was 24.1% higher than that of the older group. During the voyage, the reduction ratio of the individual walking speed was 86.0%–96.2%, and the value decreased as the deck height increased.

Keywords: Safety evacuation, Walking speed, Passenger ship, Ship motion, Experimental case

1. Introduction

Passenger ships are an important part of the maritime transport industry, especially in recent years, where the large cruise market has developed rapidly (Lois et al., 2004; Sun et al., 2018a). Although serious accidents involving passenger ships are rare, possible consequences can be catastrophic (Sun et al., 2018b; Vanem and Skjong, 2006). This has been demonstrated by accidents, such as the Ro-Ro passenger ship "Sewol" that sank near Screen Island in 2014, which caused the loss of 304 passengers and crew, who are either dead or missing (Kim et al., 2016; Kim et al., 2019). In such an accident, the effective evacuation of passengers is a last resort to reduce loss (Hystad et al., 2016; Sun et al., 2018a; 2018b). Existing evacuation analyses do not meet a satisfactory level; the accidents of the high-speed passenger catamaran "St. Malo" and the cruise vessel "Costa Concordia" are typical examples (Hystad et al., 2016). Some researchers argue that if the effects of ship motion and listing on personnel behaviour are not taken into account, evacuation analysis may be less realistic to provide appropriate guidance (Hystad et al., 2016; Lee et al., 2003).

Individual walking speed is an important parameter for passenger ship evacuation analysis as it greatly affects the results. It depends not only on the age, gender, height, and mobility of passengers but also on external factors, such as ship motion and listing (Kim et al., 2019; Lee et al., 2004). As shown in Fig. 1, a ship will oscillate in six degrees of freedom in the ocean, with the most common motions being roll and pitch. As the length of a ship is larger than its width, in general, its roll is greater than its pitch (Haaland et al., 2015; Walter et al., 2019). The impact of ship motion on individual walking is so obvious that those with experience onboard have observed that the "swing gait" of seafarers will continue for a while after returning to the land (Walter et al., 2017). Also, at a specific ship rolling angle, the farther the distance from the ship rolling centre, the greater the roll amplitude (radian), as shown in Fig. 2. Therefore, under normal circumstances, the ship's bridge rolls more than the engine room. In the process of ship rolling motion, to maintain body balance, people in different positions of the ship must adjust their posture or gait, which will affect their walking speed.

To understand the influence of ship motion on individual walking speed, a series of walking experiments were conducted on the training ship "Yupeng" of Dalian Maritime University. Individual walking speeds during berthing and sailing were collected and used to analyse the degree of influence of ship rolling motion on individual walking speeds, the difference between athwartship and fore-aft walking speeds, the relationship between Normal and fast walking speeds, and the walking speed difference between different decks. This research provides systematic research results in this field, which can be used to support, expand, and verify existing passenger ship evacuation models and simulation software; provide reliable experience data; and help crowd management during passenger evacuation.

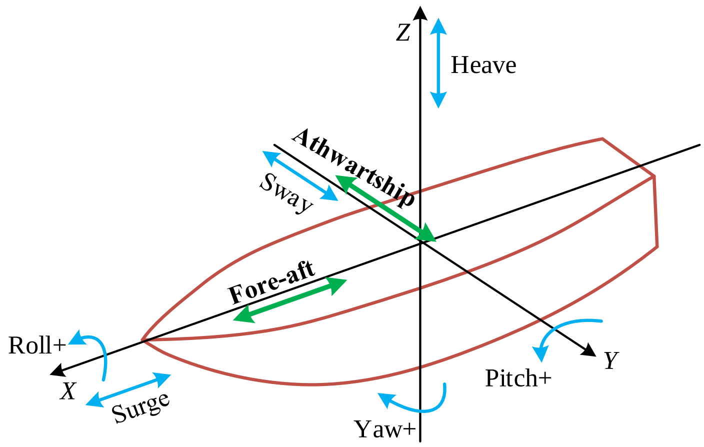

Fig. 1 Six degrees of freedom of ship motion in the ocean

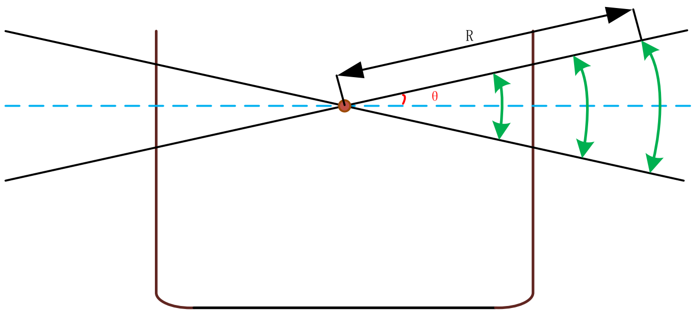

Fig. 2 Schematic diagram of ship roll amplitude on different decks

This study was conducted under natural conditions. The fact that it was not possible to control the ship motion and weather conditions inevitably reduced the level of control over the experiment. However, reducing the experimental control is helpful to understand individual walking speeds under the real ship motion, which is very helpful to solve real problems (Walter et al., 2019).

2. Related works

Since the application of the first ship evacuation model, researchers have begun to explore how to reflect the effects of ship listing and motion on human behaviour in the evacuation model (Meyer-König et al., 2007). Existing research mainly focuses on individual walking speed, which can be divided into three types: simulator experiment based on ship environment, ship trial observation, and mathematical modelling and simulation.

In simulator experiments based on ship environment, ship corridor simulators simulate different heeling and trim states of the ship, and individual walking speed changes are studied under different angles of heel. Netherlands Organization for Applied Scientific Research, TNO Human Factor conducted experimental research in a container model (4m (L) × 2.4m (W) × 2.3m (H)) attached to a hydraulic system. The study found that dynamic ship motion reduced individual walking speed by 15% (Bles, 2002). The University of Science and Technology of China (USTC) designed a ship corridor simulator of 10.0m (L) × 1.8m (W) × 2.2m (H) to test the walking speed of 17 students under the influence of ship heeling, trim, individually and simultaneously. It was found that compared with the trim angle, the heeling angle has a smaller effect on the average walking speed (Sun et al., 2018a). Fleet Technology Co., Ltd. (FTL) and the Fire Safety Engineering Group (FSEG) of the University of Greenwich jointly established a 7m (L) × 4m (W) Ship Evacuation Behaviour Assessment Facility (SHEBA) to conduct a series of experiments, and the experimental results were applied to the marine evacuation simulation software maritime EXODUS (Galea, 2012; Glen, 2004). Dalian Maritime University conducted a single pedestrian walking experiment at different rolling angles based on the six-degree-of-freedom platform of their marine rescue simulator, and they obtained data on adjustment actions, walking pauses, and the influence of rolling angle on walking (Zhang et al., 2017; ZHANG Dezhen et al., 2016).

In ship trial observations, because the ship motion cannot be controlled, researchers mostly use experimental research during ships' sailing and berthing to analyse the impact of ship motion on individual walking speed. Korea Research Institutes of Ships and Ocean Engineering (KRISO) established a corridor model of 10.0m (L) × 1.2m (W) × 1.9m (H) and placed it on a training ship of Korea Maritime University; the walking speeds of 21 students (18 males and 3 females) were tested with and without ship motion during the anchoring and berthing of the ship, and it was found that the ship motion reduced the individual walking speed by 10–20% (Lee et al., 2004). Korea Maritime University studied the walking speed of freshmen who are unfamiliar with ships on a Ro-Ro passenger ship and analysed the effect of ship motion on walking speed using ship berthing and sailing conditions; it was found that individual walking speeds during berthing and sailing were 2.02 m/s and 1.42 m/s, respectively, and the walking speed was reduced by 27.2% due to ship motion (Kwang-Il, 2013). The University of Minnesota studied the walking ability of pedestrians to walk along different directions (athwartship and fore-aft) under two ship motion patterns (roll>pitch and pitch>roll). When roll>pitch and walking along the ship's short axis or athwartship, the maximum walkable distance in the specified path should be greater than when walking along the ship's long or fore-aft axis. When pitch>roll, this relationship should be reversed (Haaland et al., 2015; Walter et al., 2017; 2019).

Researchers also used mathematical models and computer simulation techniques to study the effects of ship motion on walking gait, walking speed, and evacuation time. ITMO University established a multi-agent system to study evacuation time under certain wave conditions and at a ship speed. Due to the limitations of experimental conditions, the results of the study lacked verification, and human behavioural factors were not considered in detail (Balakhontceva et al., 2015). City University of Hong Kong established a mathematical model to analyse the characteristics of human walking under the action of ship sway. It was concluded that the parallel component of the inertial force of the ship's sway motion affects a person's walking speed in the direction of their advance, which is manifested first as acceleration and then as deceleration (Chen et al., 2016). The German Lloyd's Register of Shipping proposed a model for personnel speed reduction (*i.e.* the ratio of the individual walking speed at an angle of heel to flat walking speed) to describe the effect of different heeling or trim conditions on human walking speed; the model was applied to ship evacuation software AENEAS (Meyer-König et al., 2007).

The majority of current research on passenger evacuation in passenger ships mostly measures individual walking speeds and speed reduction through ship environment simulation devices or mathematical models. Moreover, existing ship motion platforms cannot conduct effective experimental research due to their insufficient sizes. Meanwhile, due to the impact of safety issues and limited resources available for experiments, ship trial observation data is also very limited. Therefore, there is still a need to systematically analyse the influence of ship motion on human walking speed during the evacuation of passenger ships through a ship trial to supplement and advance existing research results.

3. Experimental section

3.1 Ship profile and experimental conditions

The training ship "Yupeng" of Dalian Maritime University is equipped with a ship motion attitude tester, and the ship rolling and pitch are displayed in real time in the electronic chart display and information system (ECDIS). 80–90 cadets were on board for internships for approximately 8–10 months each year, from July to May. Table 1 summarizes the basic information of the ship.

Table 1 Specification of the "Yupeng" training ship

Category	Information	Category	Information
Ship Name:	Yupeng	Type of Ship:	Special Purpose Ship
LOA:	199.8 m	Moulded depth:	15.5 m
Max. breadth:	27.8 m	Max. height:	52.87 m
GRT:	27, 143 t	Max. Speed:	17.5 kn
Capacity:	40 seafarers, 6 teachers, 90 cadets	Navigation route:	China mainland ↔ South America ↔ South Africa

3.2 Participant information

A total of 15 persons were selected for the experiment, including 11 cadets and 4 seafarers. Their basic information is listed in Table 2. The average age of all subjects was 25.8 ± 10.5 years, their average height was 175.3 ± 6.6 cm, and their average weight was 71.3 ± 8.6 kg. The average age of the cadets was 21.5 ± 0.82 years, average height was 176.9 ± 3.3 cm, and the average weight was 70.4 ± 8.8 kg. The average age of the seafarers was 37.5 ± 16.3 years, their average height was 170.6 ± 11.3 cm, and their average weight was 74.0 ± 8.2 kg. All subjects were in a good physical condition without any disorders, such as imbalance or epilepsy.

Table 2 Basic information of the experimental subjects

No.	Height (m)	Weight (kg)	Age	Gender	Role	No.	Height (m)	Weight (kg)	Age	Gender	Role
1	180	73	22	Male	Cadet	9	174	65	21	Male	Cadet
2	172	50	21	Male	Cadet	10	179	82	22	Male	Cadet
3	178	67	23	Male	Cadet	11	175	78	22	Male	Cadet
4	178	80	21	Male	Cadet	12	160	84	46	Male	Seafarer
5	174	72	22	Male	Cadet	13	162	64	56	Male	Seafarer
6	183	70	21	Male	Cadet	14	180	73	27	Male	Seafarer
7	174	72	20	Male	Cadet	15	181	75	21	Male	Seafarer
8	179	65	22	Male	Cadet						

3.3 Experimental design

The experiment was approved by Dalian Maritime University and the captain of the training ship; it was conducted in the living area of the ship. To increase the accuracy of the experimental results, the test area (L) was larger than the calculation area (S) to reduce the impact of acceleration and deceleration processes on the results, as shown in Figure 3. Information on the state of the ship during the test period is listed in Table 3. The first experiment (Exp. 1) was performed during ship mooring alongside. The test subjects were tested for Normal walking and fast walking speeds, where Normal walking means walking comfortably and naturally, and fast walking means walking as fast as possible without running.

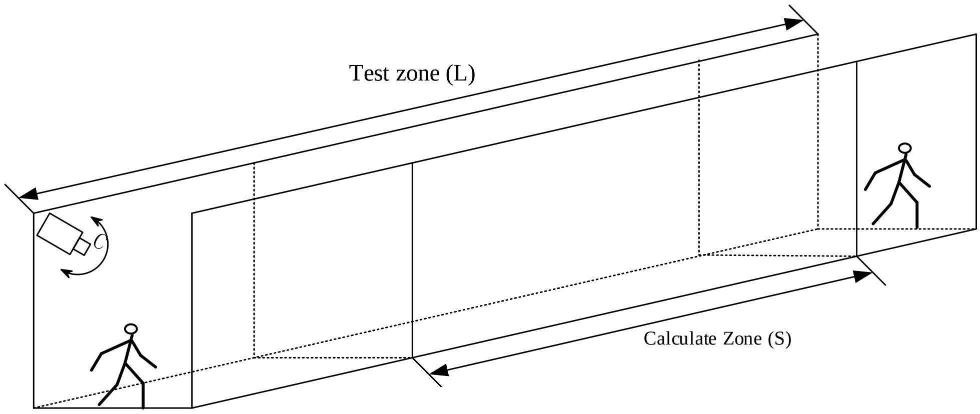

Fig. 3 Basic experimental area setup

To study the effect of ship rolling on human walking speed, athwartship and fore-aft corridors in the living area were selected as experimental areas. The test subjects were tested for Normal walking speed and fast walking speed in the experimental areas. The experiments during the voyage of the ship were divided into three groups based on the first, third, and sixth decks of the ship. Table 3 lists the state and weather information of the ship during the test. The second experiment (Exp.2) was conducted on the first deck of the ship, a bottommost deck of the living area. Normal and fast walking speeds were collected in the athwartship direction and fore-aft direction. To understand the influence of the rolling amplitude of different decks on the walking speed of personnel, Experiment 3 (Exp. 3) and Experiment 4 (Exp. 4) were conducted on the third and sixth decks, respectively. Normal and fast walking speeds were collected in the athwartship direction and fore-aft direction.

Table 3 Ship status and weather information during the experiment

Ship state	Category	Information	Category	Information
Moored alongside	Time	2019-03-05 13:00	Ship position	23°55'18"S; 046° 17'48"E
	Vessel speed (kn)	0 kn	Draft (m)	9.1 m
Navigation	Time	2019-03-27 18:00	Ship position	34°20'48"S; 018° 29'30"E
	Vessel speed (kn)	13.5 kn	Draft (m)	9.1 m
	Course (°)	C=107.3°		
	Wave scale (Beaufort) and direction	S=4, θ_s=315°	Wind scale (Beaufort) and direction	W=5, θ_w=315°
	Max. rolling angel (°)	θ_a=4°	Max. pitch angel (°)	θ_b=0.2°

3.4 Experimental procedure

During the experiment, the experimental commander issued instructions, such as Normal walking, fast walking, starting walking and stopping walking. Once subjects received instructions, they performed the required actions.

To obtain an individual's walking speed v_i, the time they took to walk through the experimental area (as shown in Fig. 4) was measured and recorded by a camera. For example, in a certain experiment, the subject entered the calculation area at time t^+ and left the calculation area at time t^-, where any part of the subject's body crossing the boundary of the calculation area was regarded as entering the calculation area, and when the body left the calculation area completely was regarded as leaving the calculation area. Then, the time interval Δt_i and walking speed v_i of the subject passing through the calculation area can be calculated as follows:

$$\Delta t_i = t_i^- - t_i^+, v_i = \frac{S}{\Delta t_i} \qquad (1)$$

where S is the length of the experimental area.

To obtain the variation law of individual walking speed in different experiments, the average walking speed $\bar{v}$ of N experimental subjects was calculated as follows:

$$\bar{v} = \frac{1}{N}\sum_{i=1}^{N} v_i \qquad (2)$$

To understand the dispersion degree of individual walking speed, formula (3) was used to calculate the standard deviation (σ) of individual walking speed.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(v_i - \bar{v})^2} \qquad (3)$$

To understand the reduction of individual walking speed caused by ship motion, the reduction ratio of individual walking speed was calculated using formula (4), that is, the ratio r of individual walking speed when there is ship motion to the speed when there is no ship motion, p is the walking pattern, such as Normal walking or fast walking, and d is the walking direction, which is athwartship or fore-aft. $r\ (p, d)$ is the walking speed reduction ratio for a certain walking pattern and direction under the presence of ship motion, $v\ (p, d)$ is the walking speed for a certain walking pattern and direction under the presence of ship motion, and $v_{normal-p}$ is the normal walking speed of an individual in a certain walking pattern without ship motion.

$$r(p,d)=\frac{v(p,d)}{v_{normal-p}} \qquad (4)$$

4. Results and discussion

A summary of the experimental results is given in Table 4. Next, the effect of ship motion on individual walking speed, the walking speed difference between athwartship and fore-aft situations, the difference in walking speed between different age groups, the ratio of Normal walking speed to fast walking speed, and the walking speed reduction are analysed.

Table 4 Experimental conditions and results

Ship state	Experiment no.	Test zone	Experimental results
Moored alongside	Exp. 1	Deck 1	Normal walking speed Fast walking speed
Navigation	Exp. 2	Deck 1	Normal walking speed (athwartship)
	Exp. 3	Deck 3	Normal walking speed (fore-aft)
	Exp. 4	Deck 6	Fast walking speed (athwartship) Fast walking speed (fore-aft)

4.1 Distribution of individual walking speeds under different conditions

The walking speeds of personnel in Exps. 1–4 were collected according to the experimental design. Fig. 4 shows the distribution of walking speed of personnel in each experiment. During the berthing period, the Normal walking speed was 1.28–1.68 m/s with an average of 1.53 m/s, and the fast walking speed was 1.50–2.14 m/s with an average of 1.95 m/s. During the voyage, on the first deck, the Normal walking speed (athwartship) was 1.32–1.59 m/s with an average of 1.47 m/s, the fast walking speed (athwartship) was 1.48–2.04 m/s with an average of 1.87 m/s, the Normal walking speed (fore-aft) was 1.28–1.64 m/s with an average of 1.42 m/s, and the fast walking speed (fore-aft) was 1.44–2.06 m/s with an average of 1.85 m/s. On the sixth deck, the Normal walking speed (athwartship) was 1.28–1.49 m/s with an average of 1.40 m/s, the fast walking speed (athwartship) was 1.40–1.84 m/s with an average of

1.69 m/s, the Normal walking speed (fore-aft) was 1.24–1.49 m/s with an average of 1.37 m/s, and the fast walking speed (fore-aft) was 1.39–1.79 m/s with an average speed of 1.67 m/s.

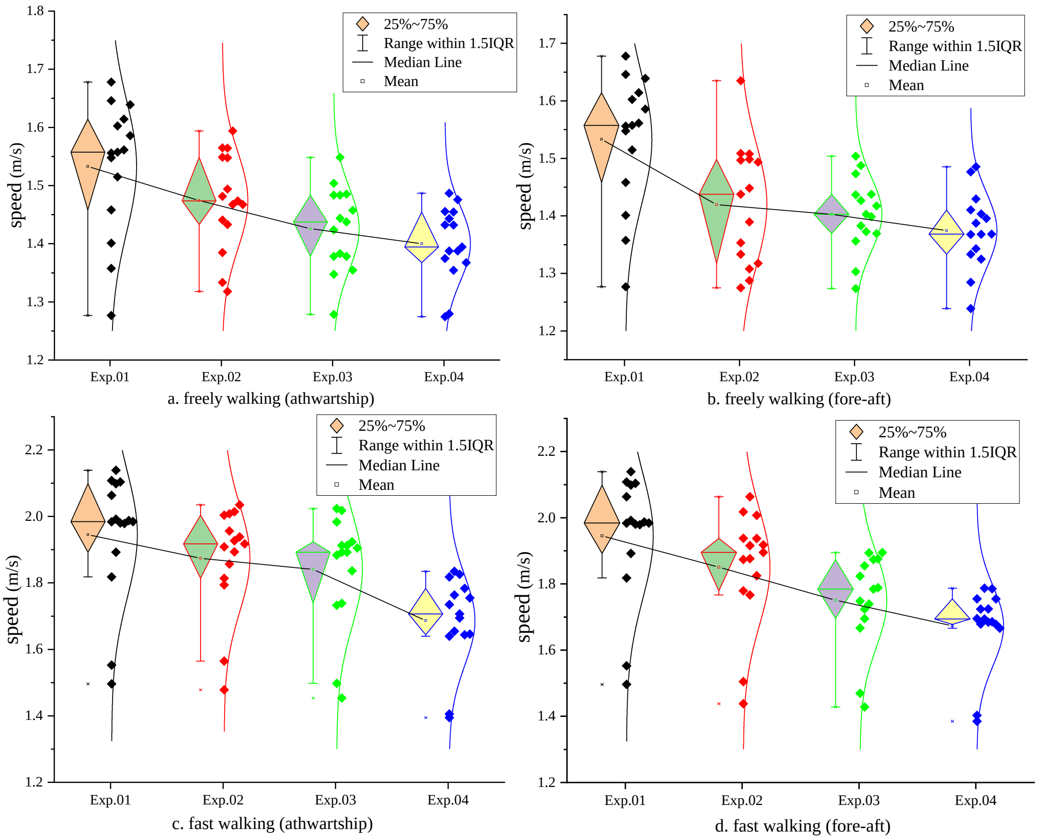

Fig. 4 Distribution of individual walking speed under different conditions

During the berthing period, the speed ranges of Normal walking and fast walking were comparable to the experimental results obtained by Sun et al. (2018a), where the fast walking speed range was 1.46–2.00 m/s and Normal walking speed range was 1.01–1.60 m/s (trim and heel angles equal to 0°), giving our experimental results a level of reliability.

In general, ship motion reduced Normal walking speed by 3.8%–10.3% and fast walking by 3.7%–14.0%. These results are similar to those of Bless et al. (2002). Compared with mooring alongside, individual walking speed during the voyage was more concentrated, which means that during the berthing period, the participants had relatively relaxed and Normal walking habits. However, human walking steps are relatively cautious and slow due to ship motion and nervousness (Kwang-Il, 2013).

Due to the influence of the ship's roll, the higher the deck (i.e., the farther the distance from the ship rolling centre), the greater the influence of ship motion on humans. To verify this conjecture, the results of Exp. 2 and Exp. 4 were compared and analysed using the non-parametric Wilcoxon rank test. The results are shown in Table 5. At the 95% confidence level, except for Normal walking (fore-aft), the results were all significant. Compared with the first deck's case, the sixth deck's Normal walking (athwartship) and fast walking speeds (athwartship) were reduced by 5.0% and 10.0%, respectively, and the Normal walking (fore-aft) and fast walking speeds (fore-aft) were reduced by 3.2% and 9.6%, respectively. Besides, fast walking is greatly affected by ship rolling, which is because people have to adjust their walking posture and slow down to maintain balance (Walter et al., 2017).

Table 5 Non-parametric test results for walking speed on the first and sixth decks

Walking pattern	Direction	Wald	Z	Significance
Normal walking	athwartship	113	2.9818	0.001
	fore-aft	92	1.78908	0.073
Fast walking	athwartship	120	3.37937	<0.001
	fore-aft	1	-3.32258	<0.001

4.2 Comparative analysis of athwartship and fore-aft walking speed

During voyage, when people stand in athwartship and fore-aft directions, the kinematics of the upright posture is very different to achieve (Varlet et al., 2015; Walter et al., 2019). Also, when walking on the ship, such as walking along the athwartship or fore-aft axis of the ship, the time intervals of gait and stride are different (Haaland et al., 2015). Therefore, the analysis of athwartship and fore-aft walking speeds will predictably reflect the influence of ship motion on actual walking ability in these two directions.

As shown in Fig. 5, as the deck height increases, the speed of athwartship and fore-aft walking gradually decreases. However, the athwartship walking speed is slightly higher than the fore-aft walking speed. In the Normal walking pattern, athwartship walking is 1.6%–3.7% faster than fore-aft walking. In the fast walking pattern, athwartship walking is 0.8%–4.9% faster than fore-aft walking. This is in line with the conclusions of related research on ship walking ability, which show that the effect of ship rolling on fore-aft walking is greater than that of athwartship walking (Haaland et al., 2015; Walter et al., 2017; Walter et al., 2019).

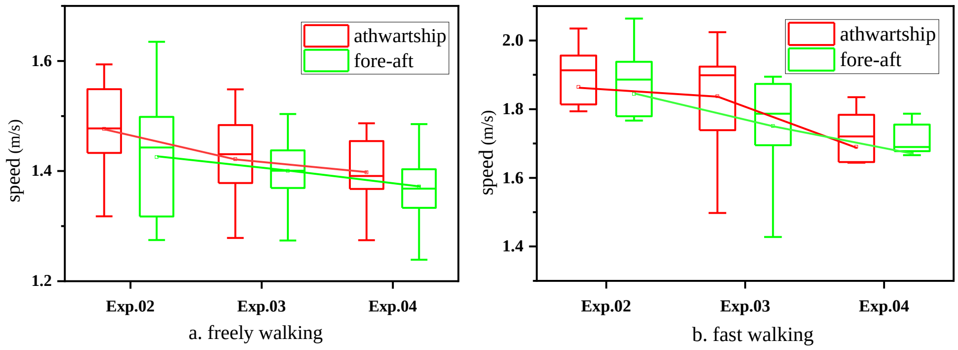

Fig. 5 Distributions of individual walking speed in athwartship and fore-aft directions

To analyse the difference between athwartship walking speed and fore-aft walking speeds, the non-parametric Wilcoxon rank test was used for Exps. 2–4. The results are shown in Table 6. At the 95% confidence level, the results of Exp. 2 (Normal walking), Exp. 4 (Normal walking), and Exp. 3 (fast walking) were significant, but the other three groups were not.

Table 6 Non-parametric test result of walking speed of the athwartship and fore-aft

Experiment No.	Walking pattern	Wald	Z	Significance
Exp. 2		100	2.24345	0.022
Exp. 3	Normal walking	78	0.99393	0.330
Exp. 4		86	2.07162	0.035
Exp. 2		90	1.67549	0.095
Exp. 3	Fast walking	106	2.58423	0.007
Exp. 4		74	0.76675	0.454

4.3 Comparative analysis of walking speed in different age groups

To analyse the effect of age on walking speed, participants were divided into a younger group (average age 21.9 ± 1.7 years) and an older group (average age 51.0 ± 7.1 years) with a partition at age 30. A comparison of the average speeds of the two groups under different experimental conditions is shown in Fig. 6. Under each experimental condition, the average walking speed of the younger group is greater than that of the older group, which reflects the effect of age on individual walking speed.

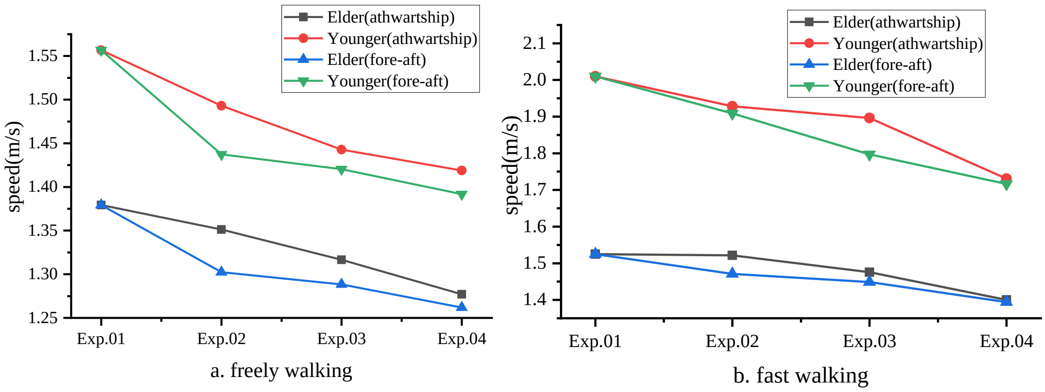

Fig. 6 Average individual walking speeds of older and younger groups

During the berthing period, the Normal walking speed range of the younger group was 1.28–1.68 m/s, while that of the older group was 1.36–1.4 m/s. The average speed of the younger group was 11.4% faster than that of the older group. The fast walking speed range of the younger group was 1.82–2.14 m/s, while that of the older group was 1.50–1.55 m/s. The average speed of the younger group was 24.1% faster than that of the older group. Compared with the walking speeds recommended by the IMO guidelines (IMO, 2016), the Normal walking speed of the younger and older groups collected in this experiment are within the speed ranges of 1.11–1.85 m/s and 0.97–1.62 m/s recommended by the IMO, respectively. Compared with the berthing period, the individual walking speeds of the two groups during the voyage were both reduced. Moreover, as the deck height increased, the Normal and fast walking speeds of the younger and older groups decreased, but the reduction ratios were different. The decrease of Normal walking (athwartship) in the older group was the smallest at 7.4% while the amplitude of fast walking (fore-aft) in the younger group was the largest at 14.6%. In the same situation, such as Normal walking (athwartship) of the older group vs Normal walking (athwartship) of the younger group, the walking speed of the younger group was reduced more than that of the older group.

To determine whether there is a significant difference in walking speed between the two groups, the non-parametric Mann-Whitney test was used on Exp. 1–4. At a 95%

confidence level, except for the Normal walking part of Exp. 1, all results were significant, indicating that the walking speeds of the younger group and older group are significantly different.

4.4 Comparative analysis of Normal and fast walking speeds

As shown in Fig. 7, as the deck height increases, the average speeds in the fast walking and Normal walking conditions show the same trend. To distinguish between Normal walking speed and fast walking speed, EXODUS (Gelea et al., 2003) uses a coefficient (0.9) to represent the ratio of individual walking speed in different walking patterns.

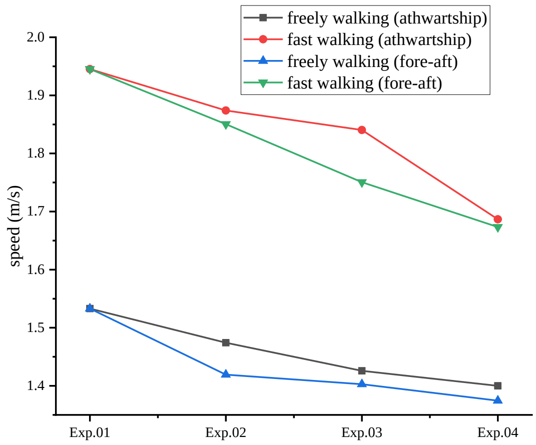

Fig. 7 Average individual walking speeds for Normal and fast walking

Considering that Normal walking and fast walking showed the same trend in the experiments, the ratios of the individual walking speeds in the Normal walking and the fast walking conditions were calculated for each experiment, and the results are shown in Fig. 8. During berthing, the ratio of Normal walking to fast walking speed was 79.2 ± 6.5%; during the voyage, the ratio was 77.1 ± 6.5% to 82.4 ± 4.0%. This is similar to the 78.6 ± 2.7% reported by Sun (2018) but is not consistent with the coefficient (0.9) used in EXODUS, which may be related to the different basic characteristics of personnel in different countries.

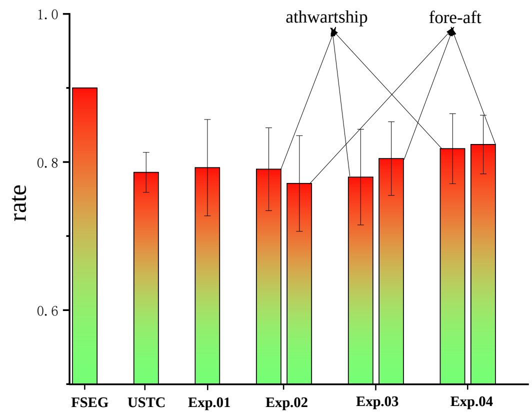

Fig. 8 Ratio between Normal and fast walking speeds compared with other institutes

4.5 Comparative analysis of walking speed reduction

In Exps. 2–4, the walking speed reduction during the voyage was 86.0%–96.2%, and the reduction decreased as the deck height increased. In general, the speed reduction ratio of Normal walking is greater than that of fast walking, and such a reduction in the fore-aft direction is greater than that in the athwartship direction.

The research results of Yoshida et al. (2001) on a 3-meter-long experimental platform found that under the influence of ship rolling, the individual walking speed reduction ratio is approximately 80%–86%, which shows the same reduction trend as the results of this experiment, but the reduction amplitude was slightly different, which may be related to the different test platforms.

When the ship's angle of heel reaches 20°, the speed reduction ratio of walking speed has been found as 69%-95% (Bles, 2002; Meyer-König et al., 2007; Sun et al., 2018a). To compare the speed reduction under ship rolling motion (dynamic) and heeling (static) conditions, a multi-coordinate axis chart was plotted, as shown in Fig. 9. The dotted line is the dynamic speed reduction ratio, and the solid line is the static speed reduction ratio. By comparison, the speed reduction caused by ship motion (rolling) in Exps. 3 and 4 is equivalent to a static heeling angle of 15°–20°. Compared with the static incline, the influence of ship motion on individual walking speed is relatively large, and this effect may be greater as the rolling angle of the ship increases.

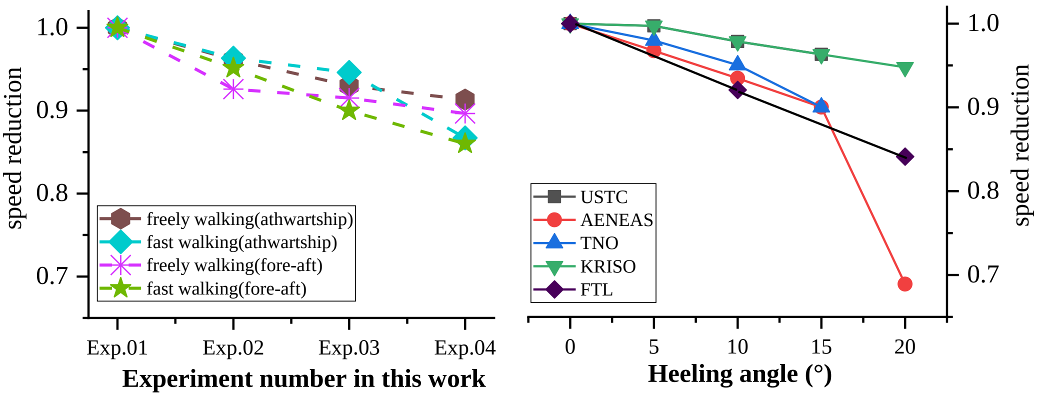

Fig. 9 Average individual walking speed reduction compared with static (heeling)

5. Conclusion

In the analysis of passenger ship evacuation, individual walking speed is an important parameter, and ship motion is an important factor affecting walking speed. To obtain the real data of ship evacuation analysis and simulation, this study used the “Yupeng” training ship of Dalian Maritime University to conduct a series of human walking experiments, and the influence of ship motion on individual walking speed was studied. It was found that during berthing, the individual Normal walking speed was 1.28–1.68 m/s, and the fast walking speed was 1.50–2.14 m/s; the ship motion reduced the speed of Normal walking by 3.8%–10.3% and fast walking by 3.7%–14.0%. During the voyage, due to the influence of ship rolling, the farther from the rolling centre, the greater the influence of ship motion on walking speed. In Normal walking conditions, athwartship walking was 1.6%–3.7% faster than fore-aft walking, and in fast walking conditions, athwartship walking speed was 0.8%–4.9% faster than fore-aft walking. According to the analysis of walking speed reduction ratio, compared with a static incline, the ship motion has a greater impact on the individual walking speed.

Although this study is valuable in the field of passenger ship evacuation, it does have some limitations and the obtained results were compared with the ones in the literature. First, a comparatively small number of samples were used in the experiments. Secondly, due to the uncontrollable ship motion, this study only collected individual walking speeds at berthing and maximum ship rolling angle of 4°. It is necessary to continue to collect the individual walking speeds in other possible conditions to supplement the existing research results. Thirdly, due to the limitations of the training ship operation, it was not possible to collect individual walking speeds of different genders and age groups. In the future, such research should be conducted if experimental conditions permit.

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