Safety Science 152 (2022) 105621

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

# An experimental analysis of the impact of thermal protective immersion suit and angle of heel on individual walking speeds

Hooshyar Azizpour[a,*], Edwin R. Galea[a,c], Sveinung Erland[a], Bjørn-Morten Batalden[a,b], Steven Deere[c], Helle Oltedal[a]

[a] Department of Maritime Studies, Western Norway University of Applied Science (HVL), Norway
[b] Department of Technology and Safety, The Arctic University of Norway (UiT), Norway
[c] Fire Safety Engineering Group, University of Greenwich, United Kingdom

ARTICLE INFO

*Keywords:*
Polar Code
Survival Suit
Walking speed
Evacuation analysis
Ship evacuation
Heel

ABSTRACT

The cold environment of Polar Regions introduces additional challenges to maritime safety in situations where it becomes necessary to abandon a vessel. The Polar Code requires all vessels operating in Polar Regions to be equipped with approved thermal protective clothing suitable for immersion in polar waters (thermal protective immersion suit (TPIS)) for all passengers and crew. However, in addition to assessing thermal protection offered by TPIS, given the criticality of time in emergencies, it is essential to understand their impact on walking performance during evacuation and how this may be impacted by adverse vessel orientation. The ARCEVAC (ARCtic EVACuation) project examines the impact of two different types of TPIS (Suit-1 and Suit-2) on walking speed at 0°, 10°, 15° and 20° angles of heel. A test facility representing a 36 m long ship's corridor was developed and 210 volunteers recruited to participate in the trials. Project findings reveal that male performed considerably better than female counterparts and increases in age, weight and heel angle had significant adverse impact on walking speed while increase in height resulted in significant increase in walking speed. Furthermore, the specific nature of the TPIS had an impact on walking speed, with the most severe reduction in walking speeds being 38% for Suit-2 and 29% for Suit-1 at 20° of heel. Reductions in walking speed of this magnitude can have a profound impact on evacuation and so cannot be ignored from evacuation analysis.

## 1. Introduction

In recent years there has been a growing popularity of large passenger ships visiting polar waters (Luck et al., 2010) and thus the potential of an incident involving these vessels in these challenging conditions has increased. In light of this, and acknowledging that the existing safety provisions for passenger ships (IMO, 2014) may not be adequate, the International Maritime Organization (IMO) recently introduced the Polar Code (IMO, 2017). As part of this, passenger ship operators are required to provide approved thermal protective clothing and insulated immersion suits (referred to as TPIS in this paper), where applicable according to the weather condition (cold and wind) for each person on-board (IMO-SOLAS, 1998).

In many passenger ship emergencies, time is a critical factor, whether it be associated with the time required to abandon the vessel, the time required to gather passengers in assembly stations, the amount of time passengers are required to remain in assembly stations or the amount of time available to move from the assembly station to the life safety apparatus (LSA). Given that emergencies may occur on passenger ships in polar waters, and that passengers and crew are likely to be encumbered by TPIS, it is essential to know how the TPIS is likely to impact time critical procedures and operations (Kruke and Auestad, 2021; Kruke, 2021). In particular, how long does it take to distribute/collect TPIS, how long does it take to don the suit and how does the wearing of TPIS impact the movement rates of passengers and crew? In most cases, apart from anecdotal information, or information from marketing materials associated with TPIS, a rigorous evidence base characterising the impact of TPIS on human performance does not exist. Furthermore, quantifying the impact of TPIS on walking and behavioural performance of passengers is critical for developing achievable evacuation procedures for passenger ships in polar waters and for modelling evacuation performance using ship-based evacuation models (Galea et al., 2013; Gwynne et al., 2003; Vassalos et al., 2002; Pradillon, 2004).

---

* Corresponding author.
*E-mail address:* azizpour.h@gmail.com (H. Azizpour).

https://doi.org/10.1016/j.ssci.2021.105621
Received 22 February 2021; Received in revised form 7 October 2021; Accepted 27 November 2021

Since 2002 (IMO, 2002) the IMO has published a set of guidelines for evacuation modelling associated with new and existing passenger ships. As part of the guidelines movement speed data associated with walking speeds in corridors and on stairs were stipulated for use in modelling. The data is based on research associated with land-based scenarios such as data collected in rail stations and other buildings. However, the IMO invited Member States to collect and submit information and data resulting from research and development activities on human behaviour associated with ship evacuation. While the movement speed data used in the current guidelines (IMO, 2016) may be appropriate for passenger ship applications under 'normal' conditions, there is no evidence to support their appropriateness to maritime situations involving adverse vessel orientation, dynamic movements associated with sea-state and the wearing of protective clothing such as TPIS. Clearly, an evidence base quantifying how these conditions may impact walking speeds is required, even if it is to demonstrate that these factors are not significant.

The Polar Code (IMO, 2017) requires vessels sailing in polar waters to provide all passengers and crew with appropriate TPIS as specified by the IMO (IMO SOLAS, 2004). However, it is essential to understand the impact that TPIS will have on other IMO requirements associated with ship evacuation (IMO, 2014). As a result, it is essential to understand how donning TPIS, walking along corridors with TPIS and walking on stairs in TPIS will impact evacuation performance, particularly in scenarios involving adverse vessel orientation (Nicholls, et al., 2012; Glen et al., 2003). To the best of our knowledge, thus far there is no study published shedding light on these issues.

To address this lack of data and amass an evidence base that can be used to assess evacuation performance in Polar Regions, Western Norway University of applied Science (HVL) and The Arctic University of Norway (UiT) embarked on the ARCEVAC (ARCtic EVACuation) project. The aim of ARCEVAC is to develop an understanding of how ship evacuation is impacted by polar conditions and suggest improvements to regulations, ship design and ship operating procedures to improve passenger ship safety while operating in polar conditions.

Here we report results from a study to quantify the impact of TPIS on walking speeds at four different angles of orientation, 0°, 10°, 15° and 20°. A total of 210 volunteers, aged between 18 and 72 years of age participated. Walking speed trials were conducted with participants wearing normal clothing and two different types of TPIS (see Supplementary Material for details). To collect the data, two test facilities measuring 36 m in length were constructed, one in Tromsø and one in Haugesund (see Supplementary Material for details).

## 2. Previous research

Many studies quantifying the performance of human walking speeds have been undertaken over the past years (e.g., (Fruin, 1971; Predtechenskii and Milinskiĭ, 1978; Boyce et al., 1999; Hwang et al., 1991), however, these have focused on movement speeds within the built environment. From the mid-1990 s, the first ship evacuation models started to appear in the literature (Vassalos et al., 2002; Galea and Owen, 1994; Galea, 2000), and these publications highlighted the need for the collection of maritime specific walking speed data, to take into consideration maritime specific aspects such as heel, trim and dynamic motions. Around this time, interest started to develop in quantifying the performance of people in maritime environments (Galea et al., 2002; Bles et al., 2002; Glen et al., 2003; Koss et al., 1997; Brumley and Koss, 2000).

Two significant land-based studies into the impact of the maritime environment on walking speeds attempted to reproduce key aspects of the maritime environment through the use of land-based simulators. Both studies occurred independently and at around the same time, one in the Netherlands at the Dutch Research Institute (TNO) (Bles et al., 2002) and the other at an industrial research facility in Canada (Glen et al., 2003).

TNO developed the Ship Motion Simulator (SMS) to generate data related to the impact of the inclination of a vessel on passenger walking speeds. The facility was rectangular in shape (a shipping container) and fitted with dividers to form three small passages some 2 m in length that required test subjects to turn at the end to enter the next leg of the passage. The rig also provided a very limited staircase capability. This again was restricted by the size of the available space. The entire facility was placed on a hydraulic platform that allowed it to be tilted to various angles of heel (up to 15°) and trim ±20°). The TNO analysis focused on the parameters of age, angle of inclination and direction of travel. Sixty subjects participated in the corridor heel experiments ranging in ages from 18 to 63 years. The data generated from this facility should be viewed with caution as the environment does not allow the development of steady-state walking speed, with participants being forced to slow down after a few steps to take a turn. The TNO analysis also did not consider gender as a potential variable. The results from this study suggest that walking speeds can be reduced up to about 15% for angles of heel up to 15° (Bles et al., 2002).

Fleet Technology of Ottawa and Fire Safety Engineering Group (FSEG) of the University of Greenwich, with funding from the Canadian Transportation Development Centre developed a facility, known as SHEBA (Ship Evacuation Behaviour Assessment) (Glen et al., 2003). The SHEBA facility allows measurements of human performance and behaviour in a typical ship passageway and stairway. SHEBA comprised of a 7 m by 4 m cabin attached to a 10 m by 2 m passageway at the end of which is a stairway. This entire structure was mounted on hydraulic rams capable of tilting the facility to up to 21°. The steel structure reproduces a ship's corridor and stair, with/without handrails. Tests were conducted with participants using life jackets and without life jackets. In subsequent developments of the SHEBA facility, tests were undertaken with reduced visibility resulting from the introduction of non-toxic smoke and a limited range of dynamic motion was introduced. Trials involving 250 participants at fixed static angles of heel ranging from 0° to 20° suggest a significant impact of *age, gender and degree of heel* on walking speed (Glen et al., 2003). Results suggest that walking speeds generally reduce with increasing angle of heel above about 10°, females experience a greater reduction in average walking speed than males with increasing angle of heel, older participants experience a greater reduction in average walking speed with increases in angle of heel than younger participants and maximum reduction in average walking speed is about 12% at 20° of heel (Galea, 2003). The negative impact of heel and trim on walking speed of individuals is also confirmed in other studies which have been conducted in smaller scale in land-based facilities (e.g., (Lee et al., 2004; Sun et al., 2018; Wang et al., 2021; Aghabayk et al., 2021). The data from both the SHEBA and SMS trials have been incorporated into maritime evacuation models (for example (Galea, 2003).

While previous studies have provided useful insight into how angle of heel may impact walking speed of individuals, all these studies have involved test subjects walking over relatively short distances, not representative of the type of distance that may be encountered in maritime applications. Furthermore, while the SHEBA trials involved participants wearing lifejackets, none of the studies have considered the impact of TPIS on participant performance at angles of heel. The SHEBA trials did reveal that wearing encumbrances such as lifejackets had an adverse effect on walking speeds at angles of heel (Galea, 2003), and so it is possible that TPIS may have an impact on walking performance. Furthermore, other studies have shown that the wearing of protective clothing and footwear can influence walking performance (Kong et al., 2013; Park et al., 2011). The nature of footwear can have a direct impact on the amount of grip the wearer has with the floor and if this is reduced, may lead to increases in the number of mis-steps and trips which consequently reduce walking speed (Chang et al., 2012; Chang et al., 2013). Furthermore, the possible negative impacts of TPIS on walking performance may be intensified with adverse vessel angle of orientation.

Indeed, regulatory authorities accept that wearing TPIS may negatively impact performance of passengers and crew and have adopted standards describing minimum performance requirements. TPIS approved by the Polar Code (IMO, 2017) must satisfy the testing and evaluation criteria recommended by the IMO (IMO SOLAS, 2004).This requires that abandonment suits can be donned, unassisted within two minutes. Furthermore, the International Organization for Standardization (ISO), in their standard for testing of immersion suits, requires that speeds measured over a distance of 30 m while wearing the immersion suit, should not be reduced by more than 25% when compared with normal walking speed (Immersion Suits Test Methods, 2012). To satisfy the regulatory requirements concerning walking speeds requires test data from only six test subjects. Clearly, with data from such a small number of participants the reliability of the walking speed analysis is questionable.

## 3. Experimental set-up and procedures

The experimental set-up and procedures are described in full in the Supplementary Material (see Supplementary Material S1 and S2). Here we provide an overview of the experimental set-up and procedures.

The test facility consisted of a corridor structure measuring 1.7 m in width, 2.2 m in height and 36 m in length. The corridor could be orientated at four different angles of heel, 0°, 10°, 15° and 20°. Two test facilities were constructed, one at the ARCOS safety centre in Tromsø (see Fig. 1), constructed from construction site corridor containers, and one at the ResQ safety center in Haugesund (see Fig. 2) constructed from wood (see Supplementary Material S1.1 for details).

For each angle of heel three types of clothing conditions were explored in which the participants wore either their normal clothing, identified as Suit-0, or a lightweight survival suit produced by Hansen Protection (Sea Pass passenger suit) identified as Suit-1 or an immersion suit with fully integrated buoyancy and thermal insulation produced by Viking (Yousafe Blizzard PS5002) identified as Suit-2 as depicted in Fig. 3 (see Supplementary material S1.2 for details). Participants were instructed to wear flat shoes to the trials. Both suits are of a ‘one size fits all’ design. For Suit-1 shoes could be worn either inside or outside the suit while for Suit-2, shoes were not to be worn.

Participants were assigned into groups associated with a suit type (three groups) and into sub-groups associated with heel angle (10°, 15° or 20°). Each participant was required to walk through the corridor, one person at a time, as quickly as possible without running (see Supplementary material S2 for details). On completing their passage through the corridor, the next participant would repeat the process. Participants were not permitted to observe others attempting to walk through the corridor. On completing their first passage through the corridor, participants completed a questionnaire designed to explore their experience (see Supplementary material S3 for details). Once all the participants within a group had completed the questionnaire, they repeated the process at 0° of heel. Thus, each participant generated two walking speed data points. The behaviour and performance of the participants as they passed through the corridor was recorded by three GoPro cameras installed at three locations in the corridor, one positioned to record the starting time, one positioned to record the time at which they crossed the centre line and one to record the time at which they crossed the finishing line (see Supplementary Material S2.4 for details). The cameras were also used to record behaviour of the participants as they passed through the corridor (see Fig. 4). In total, four categories of data were collected during the experiment, demographical/registration, walking speed (video), behavioural (video and questionnaire) and perceptions (questionnaire).

In total 210 participants were recruited for the trials, 125 in Tromsø and 85 at Haugesund (see Supplementary Material S2 for details). The trial design partitioned participants into three age groups (AG),

**Fig. 1.** The Tromsø test facility heeled at $20^0$.

**Fig. 2.** The Haugesund test facility heeled at $20^0$.

**Fig. 3.** Hansen Protection (Suit-1) and Viking Immersion suit (Suit-2).

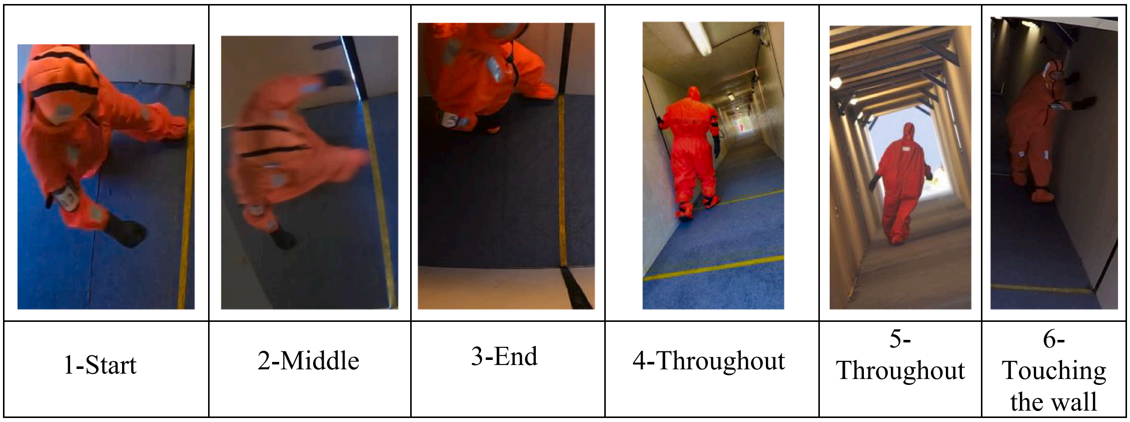

1-Start
2-Middle
3-End
4-Throughout
5-Throughout
6-Touching the wall

**Fig. 4.** Still images captured from trial video footage depicting the progress of participants at different stages of their movement through the heeled corridor.

**Table 1**
Total number of participants in each category including age groups (AG), following removal of disqualified participants.

| Suit Type | Gender | 0° Heel AG1/AG2/AG3 | 10° Heel AG1/AG2/AG3 | 15° Heel AG1/AG2/AG3 | 20° Heel AG1/AG2/AG3 | Total (Excluding 0°) |
|---|---|---|---|---|---|---|
| Suit-0 | Male | 28/18/11 | 7/3/2 | 6/5/2 | 15/10/7 | **57** |
| | Female | 16/5/4 | 2/0/2 | 5/2/0 | 9/3/2 | 25 |
| | **Total** | **44/23/15** | **9/3/4** | **11/7/2** | **24/13/9** | **82** |
| Suit-1 | Male | 10/3/13 | 6/2/3 | 0/0/0 | 4/1/10 | 26 |
| | Female | 6/10/3 | 1/4/2 | 0/0/0 | 5/6/1 | 19 |
| | **Total** | **16/13/16** | **7/6/5** | **0/0/0** | **9/7/11** | **45** |
| Suit-2 | Male | 18/11/2 | 7/3/1 | 0/0/0 | 11/8/1 | 31 |
| | Female | 11/11/4 | 4/4/1 | 0/0/0 | 7/7/3 | 26 |
| | **Total** | **29/22/6** | **11/7/2** | **0/0/0** | **18/15/4** | **57** |
| Overall Total | | **89/58/37** | **27/16/11** | **11/7/2** | **51/35/24** | **184** |

$AG1 \in (18-29)$, $AG2 \in (30-50)$ and $AG3 \in (50+)$. Attempts were made to have equal numbers in each age group and equal numbers of males and females however, this proved difficult. The distribution of age and gender within each suit and heel category is shown in Table 1. The data collection and data handling procedures were approved by the Norwegian Centre for Research Data (NSD) (see Supplementary Material S2.4 for details).

## 4. Results and data analysis

### 4.1. Data extraction

The process by which the walking speed data was extracted from the video footage is detailed in Supplementary Material S4. This involves extracting the time at which the participant crossed the start-line, the mid-point line and the end-line with times measured to an accuracy of ± 0.04 second. The number of times the participant touched the confining walls of the corridor was determined and in addition the number of missteps and falls was recorded (see Supplementary Material S4.1). Extraction of video data required approximately 190 person hours of effort.

Several participants were disqualified from the analysis for one of two reasons (see Supplementary Material S4.3 for details). During video analysis it was noted that a number of participants were 'running' even though they had been instructed to walk and not run. Running was defined as travelling at 3 m/s or greater (Glen et al., 2003; Koss et al., 1997; Brumley and Koss, 2000). The data from these participants were removed from the analysis. Furthermore, some participants were found to walk faster when at heel than at 0°. As heel is expected to have a neutral or negative impact on walking speeds, if the walking speed at 0° heel was found to be slower than 90% of their speed at heel, the data from these participants were also removed as it was considered that these participants were not fully engaged in the entire trial. Through this process data from 10 participants at 10°, 5 participants at 15°, and 11 participants at 20° were removed from the analysis. In total, data from 26 participants were removed, creating a data-set from 184 participants. The possible impact on results of analysis caused by removing aforementioned participants is discussed in Supplementary Material S4.3. Presented in Table 1 is a summary of the number of participants whose data contributed to the analysis.

Prior to the disqualification of 26 participants, a total of 18,480 data points were collected from the 210 registered participants, with 16,192 data points remaining following the removal of the disqualified participants.

### 4.2. Analysis of speed data and descriptive statistics

As data were collected at two sites (125 in Tromsø and 85 at Haugesund) the potential influence of trial location on mean walking speed was assessed to determine whether the two data-sets could be merged. A distribution identification test was conducted, and the Anderson-Darling test showed that the walking speed data derived from both sites were best represented by normal distributions with P-values of 0.36 and 0.14 for locations in Tromsø and Haugesund, respectively. Results from a

**Table 2**
Arithmetic mean and standard deviation of different groups according to suit type, gender and angle of heel.

| Mean Speed (m/s) (Standard Deviation) | | 0° Heel | 10° Heel | 15° Heel | 20° Heel |
|---|---|---|---|---|---|
| Suit-0 | Male | 2.32 (0.32) | 2.53 (0.35) | 2.20 (0.28) | 2.11 (0.28) |
| | Female | 2.22 (0.21) | 2.10 (0.32) | 2.02 (0.31) | 2.01 (0.37) |
| Suit-1 | Male | 2.36 (0.34) | 2.45 (0.33) | NA | 1.71 (0.41) |
| | Female | 2.12 (0.26) | 2.16 (0.21) | NA | 1.60 (0.22) |
| Suit-2 | Male | 2.26 (0.28) | 1.92 (0.26) | NA | 1.78 (0.39) |
| | Female | 2.02 (0.24) | 1.80 (0.28) | NA | 1.41 (0.25) |

**Table 3**
Definition and range of factors contributing to walking speed (according to the collected data).

| Variable | Definition (Unit) |
|---|---|
| $x_1$ | Age ($x_1 \in 18-72$ years old) |
| $x_2$ | Gender ($x_2 \in$ Male $= 0$, Female $= 1$) |
| $x_3$ | Angle ($x_3 \in 0^\circ$ to $20^\circ$) |
| $x_4$ | Using Suit-1 ($x_4 \in$ Yes $= 1$, No $= 0$) |
| $x_5$ | Using Suit-2 ($x_5 \in$ Yes $= 1$, No $= 0$) |
| $x_6$ | Height ($x_6 \in 154-195$ cm) |
| $x_7$ | Weight ($x_7 \in 48-123$ kg) |

two-sample T–test showed that the influence of location of trial is not significant at a 5% significance level for mean speed values. Therefore, the two data-sets were merged. Furthermore, analysis showed that there was no significant difference between the average walking speed of individuals in first and second half of the corridor and so fatigue did not impact walking speeds (see Supplementary Material S4.2 for details).

In total 368 walking speed data points were collected from the 184 participants. Descriptive statistics (mean, standard deviation) for the data-set are presented in Table 2. The results suggest that, with the exception of a blip at 10° of heel, there is a general decrease in mean walking speed as the angle of heel increases. However, to determine how various factors such as age, gender and suit type impact walking speed as the angle of heel increases, requires the development of a regression model.

### 4.3. Regression model

Studies have shown that the correlation between walking speed ($Y$) and its predictors, such as age and gender of the individuals and angle of heel of the space is not necessarily linear (Glen et al., 2003). A method for handling non-linear relationships between variables is logarithmical (log) transformation of dependent and/or independent variables (Benoit, 2011). If the response variable (i.e., walking speed) is log-transformed, the effect of any predictor in a linear regression model would be a percentagewise reduction or increase in walking speed. Moreover, the potential for predicting negative walking speed is avoided. In our case, the log-transformation resulted in a more symmetrical distribution of the residuals, and an improved fit to the data, indicated by an increase in the value of R-squared. A log-linear multiple regression model for response variable $Y$ (i.e., walking speed) and predictors $x_i$ can generically be represented as follows:

$$\mathrm{Ln}(Y) = a_0 + a_1x_1 + a_2x_2 + \cdots + \varepsilon, \tag{1}$$

where $\varepsilon \sim \mathrm{Normal}(0, \sigma)$

By exponentiation of Eq. (1) we have:

$$\begin{aligned} Y &= e^{a_0} * e^{a_1x_1} * e^{a_2x_2} * \cdots * e^{\varepsilon}, (\text{if we take } e^{a_i} = A_i) \text{ Then :} \\ Y &= A_0 * A_1^{x_1} * A_2^{x_2} * \cdots * \widetilde{\varepsilon},\ \widetilde{\varepsilon} \sim \mathrm{logNormal}(0, \sigma) \end{aligned} \tag{2}$$

In the log-linear regression model, each 1-unit increase in predictor $x_i$ multiplies the expected value of $Y$ by $e^{a_i} = A_i$. Here $A_i$ can be interpreted as a growth factor, and $(A_i - 1)$is the relative increase in walking speed per unit increase of $x_i$ (all other factors being kept constant). $Y$ may be dependant not only on the predictors $x_i$ but also on the interaction between predictors. The interactions between predictors can be represented by the terms $x_i * x_j$ with corresponding growth factor $A_{i \times j}$ in Eq. (2).

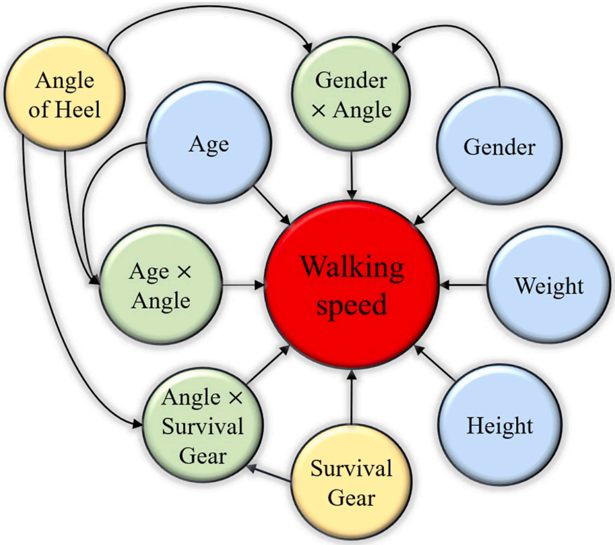


**Fig. 5.** Correlation between different factors in the log-linear regression model that significantly influence walking speed according to the collected data.

### 4.4. Impact of different variables – regression modelling

While there is a certain degree of randomness in walking speed of individuals, there is a number of personal factors that have been shown to have an impact on walking speed such as age, gender, height, weight and environmental factors such as angle of heel and trim (as discussed in (Park et al., 2011; Chang et al., 2012; Kim and Steinfeld, 2019; Shiwakoti et al., 2019; Lei and Tai, 2019; Heliövaara et al., 2012). In addition, we postulate that the nature of the TPIS worn by the individual – another environmental factor– may also impact walking speed. For the range of quantified variables presented in Table 3, the influence of each of the variables as well as the impact of their pairwise interaction on walking speed was investigated using stepwise log-linear regression (Rawlings et al., 2001), based on the regression model in Eq. (2). The regression analysis was performed using Minitab (version 19.2).

The result of the stepwise log-linear regression analysis for the estimation of walking speed can be represented by a Bayesian Belief Network (BBN) (Cooper and Herskovits, 1991). The BBN in Fig. 5 represents the causal relationships between the predicting factors which appeared to have significant influence on walking speed at a 5 % significance level. In the presented BBN model, walking speed is coloured in red while the impact of the personal and environmental variables is shown in blue and yellow respectively. Interaction terms, presented as green nodes, show that walking speed of different gender and age groups are not equally influenced by change in angle of heel. Furthermore, the negative impact of TPIS on walking speed changes with change in angle of heel.

According to the regression model presented in Section 4.3, multiple log-linear multiple regression was undertaken linking walking speed with the various influencing factors. According to the regression model, walking speed is presented as a product of different influencing factors and a random error term in Eq. (3).

$$Y = 1.5872 * 0.9982^{x_1} * 0.9323^{x_2} * 0.9999^{x_1 * x_3} * 0.9969^{x_2 * x_3} * 0.9928^{x_3 * x_4} * 0.9392^{x_5} * 0.9898^{x_3 * x_5} * 1.0037^{x_6} * 0.9975^{x_7} * \widetilde{\varepsilon},\ \text{where } \widetilde{\varepsilon} \sim \mathrm{logNormal}(0, 0.1463). \tag{3}$$

**Table 4**
Change in walking speed given one unit increase in each of the influencing variables (when all other variables are fixed).

| Variable | Definition | $a_i$ | SE : $a_i$ | $A_i$ | Change in speed per unit increase | T-value | P-value |
|---|---|---|---|---|---|---|---|
| $x_1$ | Age | −0.001815 | 0.000564 | 0.9982 | −0.18% per year | −3.22 | 0.001 |
| $x_2$ | Gender | −0.0701 | 0.0289 | 0.9323 | −6.8% for females | −2.43 | 0.016 |
| $x_5$ | Suit-2 | −0.0627 | 0.0223 | 0.9392 | −6.1% with Suit-2 | −2.81 | 0.005 |
| $x_3 \times x_1$ | Angle × Age | −0.000112 | 0.000031 | 0.9999 | −0.01% per degree ∗ year | −3.67 | <0.001 |
| $x_3 \times x_2$ | Angle × Gender | −0.00309 | 0.001552 | 0.9969 | −0.31% per degree for females | −1.99 | 0.047 |
| $x_3 \times x_4$ | Angle × Suit-1 | −0.00721 | 0.00168 | 0.9928 | −0.7% per degree with Suit-1 | −4.3 | <0.001 |
| $x_3 \times x_5$ | Angle × Suit-2 | −0.01021 | 0.00188 | 0.9898 | −1.0% per degree with Suit-2 | −5.44 | <0.001 |
| $x_6$ | Height | 0.00372 | 0.00133 | 1.0037 | 0.37% per cm | 2.79 | 0.006 |
| $x_7$ | Weight | −0.002489 | 0.000654 | 0.9975 | −0.25% per kg | −3.8 | <0.001 |

Note: SE = Standard Error (of the coefficient $a_i$).

Given the variables defined in Table 3, the log-linear regression model can predict the walking speed with $R^2 = 49.9\%$, which means that the model can explain about 50% of variation in walking speed. This degree of correlation is considered relatively high as there are many random effects that could influence the walking speed of an individual in a particular experiment. These also include, e.g., level of calf/quadriceps strength, hip flexion/abduction, impact of adrenaline, etc. (Inoue et al., 2017) which are challenging to quantify and were not measured in this experiment.

The predictors (Fig. 5), log-linear regression model coefficients ($a_i$), corresponding Standard Error (SE) terms, and the respective coefficients ($A_i$) in Eq. (3) are described in more detail in Table 4. The table presents how the walking speed is affected by the increase in each of the influencing variables by one unit when all other variables are held constant. Note that the only predictor that increases walking speed is participant height, i.e., an increase in height results in an increase in walking speed, whereas all the other predictors have a negative impact on walking performance. Similarly, synergies between age, gender, survival suit and angle of heel adversely affect walking speed (presented as green nodes in Fig. 5). All the aforementioned variables had a significant influence (at the 5% significance level as seen by the P-values in Table 4) on walking speed.

Table 4 also indicates that at 0° of heel, females walked on average 6.8% (i.e., $1 - A_2 = 1 - 0.9323$) slower than their male counterparts. Furthermore, females walk 0.31% ($1 - A_{3\times2} = 1 - 0.9969$) slower for each degree increase in angle of heel. This is represented through the Angle × Gender term which generates an additional reduction term for females when they walk on a heeled surface. The combined effect, e.g., at 10° heel, results in females walking approximately 9.6% $(1 - (0.9323 \times 0.9969^{10}))$ slower than males of the same age, weight, height who are wearing the same TPIS.

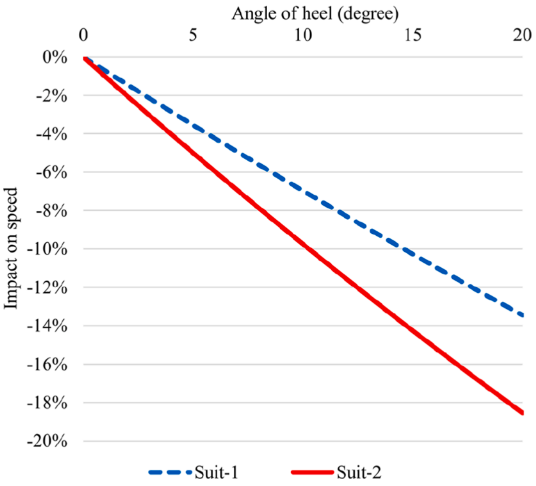
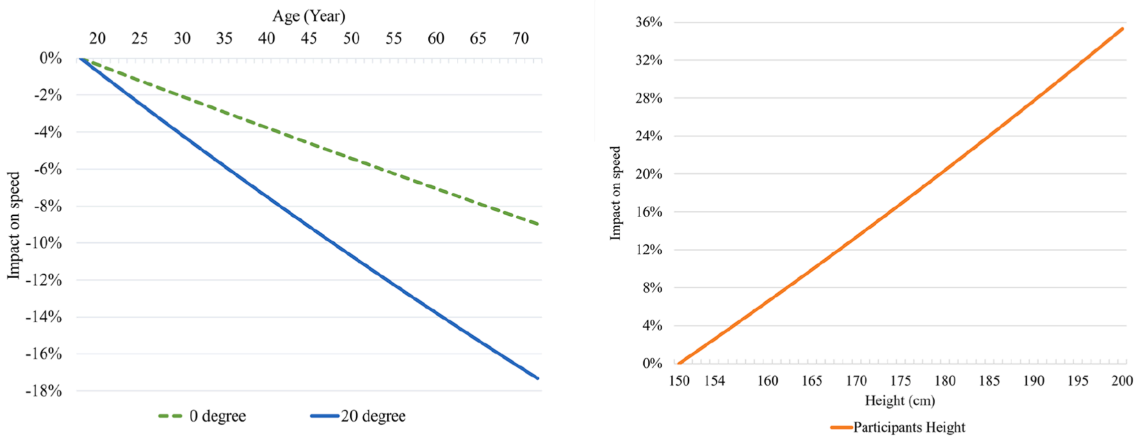


**Fig. 7.** Percentage of reduction in walking speed for different survival suit as a function of angle of heel.

The estimated effects of the continuous variables age and height on walking speed according to Eq. (3), are depicted in Fig. 6(a) and Fig. 6(b), respectively. As can be seen, as summing all other variables remain unchanged, at 0° of heel, increasing age from 18 to 72 years will reduce the walking speed by about 9% while at 20° of heel the reduction is



(a) Impact of Age on walking speed

(b) Impact of Height on walking speed

**Fig. 6.** Impact of participants (a) age and (b) height on walking speed at 0° and20° of heel.

about 17%.

Note that the additional adverse effect of age that increases with higher angle of heel, is due to the interaction term Angle × Age. In contrast, an individual with height 190 cm would walk about 21% faster than a person of height 160 cm both at 0° and 20° of heel (since there is no significant correlation between height and angle of heel, this impact remains unchanged in different angles). Presented in Fig. 7 is the reduction in walking speed only as a function of angle of heel and suit type, without the interaction of other variables. Over the specified range of the continuous variables within the collected data, the maximum changes in walking speed are, an increase of over 31% due to increase in height and a maximum decrease in walking speed of about over 18% (at 20° of heel) due to interaction of Suit-2 and angle of heel.

Similar to age and weight, angle of heel and the wearing of survival suit produced a negative impact on walking speed. The effect of the interaction between angle of heel and the two different survival suits on walking speed (using Eq. (3)) is presented in Fig. 7. The impact of Suit-1 and Suit-2 increases significantly with angle of heel (see Fig. 7). However, Suit-2 had the greater impact decreasing walking speed by 18% at 20° compared to its performance at 0°. In contrast, Suit-1 decreases walking speed by 13%. The additional adverse effect of Suit-2 in 0° of heel is discussed in Section 5.

### 4.5. Analysis of behavioural data

Analysis of the video footage also revealed the number of times participants miss-stepped (slipped) and reached out with either one hand or both hands for support from the wall (hand wall contact or HWC) at least once during their journey along the corridor (see Supplementary Material S4.1 for details).

Presented in Table 5 is a summary of the percentage of participants who slipped/miss-stepped (slipped) or reached out for the support from the wall (HWC). As can be seen there is little or no slips for Suit-0 while for both Suit-1 and Suit-2 there are many slips with the frequency increasing with angle of heel. While at 20° of heel, both Suit-1 and Suit-2 result in approximately 90% of participants slipping, Suit-2 generates considerably more slips at lower angles of heel. It is noted that while Suit-1 produces no slips at 0° of heel, almost 20% of the participants in Suit-2 slip at 0° of heel.

Table 5 also shows that as the angle of heel increased, the frequency of participants who required to touch the wall for support also increased. This trend occurs for all three suit types but is more pronounced for Suit-1 and Suit-2 at high angles of heel (20°), suggesting that participants were less stable at high angles while wearing the protective clothing.

Participants answers to questions in the post-trial questionnaire reflecting their opinion concerning the influence of different environmental factors on their walking speed. The impact that different features of the TIPS had on walking performance was assessed using a five-point Likert scale (see Supplementary Material S3 and S3.1).

In total six factors that potentially impacted walking performance while wearing the suit were considered. These were: fit of the suit, ability to hear, ability to move with the suit, comfort of footwear, ability to see and weight of the suit. Collapsing the two negative ratings (very negative and negative) we find that Suit-2 scores consistently higher negative ratings than Suit-1 across all factors. For 'fit of the suit', Suit-2 had 1.6 times higher negative score than Suit-1 and this increased to a 18.5 times higher negative score of the factor 'weight of the suit'. The highest negative score was for 'comfort of footwear' with Suit-2 scoring 96%.

**Table 5**
Percentage of participants who slipped and who made hand-wall contact (HWC).

| Suit Type | Angle of heel | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0° | | 10° | | 15° | | 20° | |
| | Slip | HWC | Slip | HWC | Slip | HWC | Slip | HWC |
| Suit-0 | 0% | 0% | 0% | 12% | 0% | 60% | 2% | 63% |
| Suit-1 | 0% | 0% | 18% | 10% | NA | NA | 89% | 100% |
| Suit-2 | 19% | 7% | 45% | 40% | NA | NA | 92% | 100% |

## 5. Discussion

### 5.1. The impact of TPIS on walking speed

While the current IMO evacuation analysis guidelines (IMO, 2016) do not require the analysis of evacuation scenarios involving adverse angles of orientation, Eq. (3) provides a means for determining walking speeds as a function of orientation (angle of heel) and nature of protective clothing, for population specifics of age, gender, height and weight. Thus Eq. (3) incorporates two environmental factors (angle of heel and type of protective clothing) into the determination of walking speeds for maritime evacuation analysis. This capability is particularly useful when evacuation modelling is used to analyse accident scenarios.

However, the primary research question that this work addresses is to quantify the impact that TPIS has on movement speeds. This is of importance when undertaking passenger ship evacuation analysis. Clearly, if wearing TPIS significantly impacts movement speeds, this will need to be factored into evacuation analysis, where time is critical. Currently, evacuation analysis required by IMO (IMO, 2016) only considers the vessel at 0° of heel and so walking speeds within the IMO guidelines are only specified for this condition. If the angle of heel is set to 0° in Eq. (3) we have:

$$Y = 1.5872 * 0.9982^{\text{Age}} * 0.9323^{\text{Gender}} * 1.0037^{\text{Height}} * 0.9975^{\text{Weight}} * 0.9392^{\text{Suit}-2} * \widetilde{\varepsilon}, \text{where} \quad \widetilde{\varepsilon} \sim \text{logNormal}(0, 0.1463) \tag{4}$$

From Eq. (4) we note that Suit-1 does not impact walking speed at 0° of heel while Suit-2 does have an impact. If we compare walking speeds in Suit-2 with those of Suit-0 we find that walking speeds are reduced by a factor of 6.1% at 0° of heel. At 20° of heel, walking speeds are reduced by about 24%. Thus, if TPIS are worn by passengers from the start of the assembly process, walking speeds can be adversely affected, even at 0° of heel, which can have a negative impact on assembly times. Thus, when we consider the impact of TPIS, we have to consider the type of suit worn and the impact this may have on walking performance. The reason for the difference in performance of the two types of suit is complex, however, some insight into the causes of these differences may be found in the behavioural and survey responses.

From analysis of the video footage, 19% of participants who wore Suit-2 slipped (see Table 5) even at 0° of heel while none of the participants slipped in Suit-0 or Suit-1. Thus, the footwear provided by Suit-2 clearly impedes movement. As can be seen in Table 5, the proportion of participants slipping while wearing Suit-2 increases as the angle of heel increases reaching 92% at 20° of heel. While the slippage proportion for Suit-1 also increases as heel angle increases, it does so at a lower rate. These observations are consistent with the trends observed in Fig. 7 where Suit-2 generates lower walking speeds than Suit-1 at all angles and the degradation in performance increases as the angle of heel increases.

From observation of the video footage and the actual trials, the slippage caused by both Suit-1 and 2 is thought to be due to either to the foot/shoe of the participant slipping inside the boot of the suit or the sole of the suit footwear not providing sufficient grip to the floor surface. Participant foot slippage inside the suit is thought to be due to the ‘one size fits all’ concept resulting in the boot of the suit being too large for many people. This occurred even though all the participants had the ankle straps secured prior to the start of their journey down the corridor. The problem of the poor fitting boot became more apparent as the angle of heel increased.

In addition, replies to the participant questionnaire support the view that Suit-2 created a greater impediment to rapid movement compared to Suit-1. Suit-2 scored higher negative ratings on all measures dealing with how the suit impacted walking performance (see Supplementary Material S3.2). This scored poorly on matters concerning the ‘weight of the suit’ – 18.5 times higher negative score than Suit-1 and 2.1 times higher negative score for ‘comfort of footwear’. Analysis of open comments in the survey showed that bulkiness of Suit-2 was another factor which negatively influenced walking speed of 73% of male and 70% of female participants. While some of these negative factors may be unavoidable due to the need to provide enhanced thermal protection, issues associated with the footwear are considered important as they can provide a significant impediment to safe evacuation and should be addressed through improved design.

### 5.2. *Walking speed data-set suitable for IMO evacuation analysis*

Within the IMO guidelines for evacuation analysis (IMO, 2016) unhindered mean walking speed for individuals at 0° of heel are specified as a function of two personal parameters, age and gender. The regression analysis presented in this paper consisted of an additional two personal parameters, weight and height. To make this regression analysis more compatible with the current IMO expectations, the regression analysis was repeated removing the two additional personal parameters. Thus, within the simplified IMO compatible walking speed model, four predictors are included, two personal predictors (age and gender) and two environmental predictors (angle of heel and suit type).

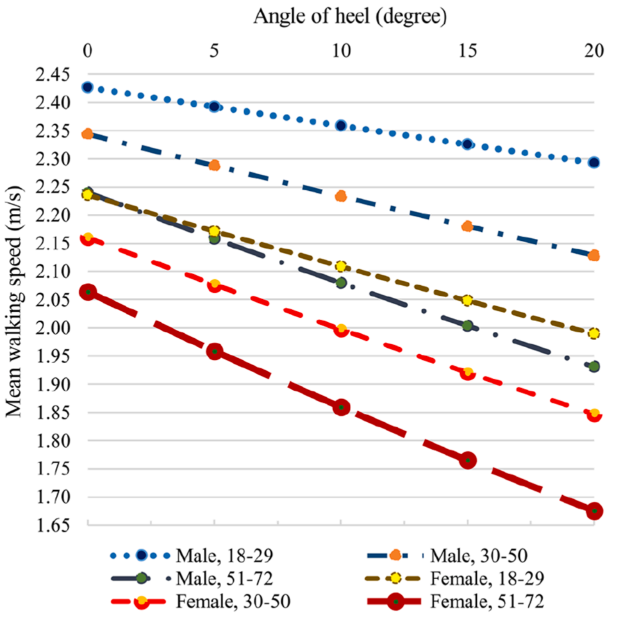


**Fig. 8.** Comparison of mean walking speed without TPIS generated by the simplified regression model (Eq. (5)) based on age, gender and angle of heel.

In the new (simplified) regression model, all parameters and introduced interactions were significant (at the 5% significance level) with the exception of the Angle × Gender interaction (P-value = 0.07). This is the result of omitting two of the significant factors (height and weight) that compromised the P-value for the interaction term Angle × Gender (which was significant in the original model). In the simplified model, the Angle × Gender interaction term has been retained and so the simplified model is given by:

$$Y = 2.55*0.9979^{\text{Age}}*0.9213^{\text{Gender}}*0.9999^{\text{Angle}*\text{Age}}*0.9970^{\text{Angle}*\text{Gender}}*0.9934^{\text{Angle}*\text{Suit}-1}*0.9363^{\text{Suit}-2}*0.9901^{\text{Angle}*\text{Suit}-2}*\widetilde{\varepsilon};\ \text{where}\ \ \widetilde{\varepsilon}\sim\text{logNormal}(0,0.1495) \tag{5}$$

The simplified model given by Eq. (5) predicts the walking speed with $R^2 = 47.4\%$, which is close to the $R^2$ produced by the original model in Eq. (4) (49.9%). To obtain the mean walking speed for individuals not wearing suits, the terms for Suit-1 and Suit-2 in Eq. (5) were set to zero (i.e., Suit-1 = 0, Suit-2 = 0), and as a result, the last three factors are equal to 1. Based on this, the mean walking speed as a function of age, gender and angle of heel that is presented in Fig. 8, suggests that average travel speeds without TPIS generally decrease with increasing angle of heel for all age groups. Furthermore, for males the decrease in average walking speed from 0° to 20° of heel is 6%, 9% and 14% for age groups 18–29, 30–50 and 51–72 respectively. For females the reductions in average walking speed are 11%, 14% and 19% for the three age groups, respectively. We note that these results are in broad agreement with the SHEBA data-set (Galea, 2003; Lee et al., 2004), in particular, that walking speeds generally reduce with increasing angle of heel, females experience a greater reduction in average walking speed than males with increasing angle of heel, older participants experience a greater reduction in average walking speed with increases in angle of heel than younger participants and the maximum reduction in average walking speed in the SHEBA trials was about 12% at 20° of heel.

The walking speeds generated by the simplified model (Eq. (5)) for 0° of heel and Suit-0 generally agree with the walking speed data presented within the IMO evacuation analysis guidelines (IMO, 2016). In particular, mean travel speed decrease with increase in age and males are on average faster than females. However, within the guidelines, the unhindered walking speed ranges between a minimum 0.56m/s for females older than 50 years of age up to a maximum of 1.85m/s for males younger than 30 years of age. In comparison, the minimum walking speed determined by the simplified model is 1.74 m/s (female, age group 51–72 years of age, 0° heel, Suit-0), while the maximum walking speed is 2.85 m/s (male, age group 18–29 years of age, 0° heel, Suit-0). Thus, the mean walking speed predicted by the simplified model (based on the data collected in the trials) for all age groups for both males and females are bigger than the mean walking speed values specified in the IMO guideline document (Vassalos et al., 2002). Furthermore, the actual walking speed measured during the trials (at 0° of heel for Suit-0) ranges between 1.73 m/s and 2.99 m/s. Thus, the minimum and maximum walking speeds measured in the trials are about respectively 67% and 38% greater than the corresponding minimum and maximum walking speed specified within the IMO guidelines document (Vassalos et al., 2002).

Given that a there was a good mix of genders (62% male and 38% female) and a reasonable mix of ages (48% 18–29 years of age, 32% 30–50 years of age and 20% 51–72 years of age) it is not clear why the measured walking speeds are so much greater than those typically used in evacuation modelling. However, it is suggested that this could be due to all trial participants being recruited from a healthy and physically fit population. The vast majority of the participants were Norwegian (90%), with average height/weight of 181 cm/85 kg and 167 cm/68 kg, and average Body Mass Index (BMI) of 26 (SD = 4.08) and 24.29 (SD = 3.42) for male and females respectively. Furthermore, the majority of both males (75 %) and females (76%) claimed that they worked out two to five times a week. Thus, the trial group are not necessarily representative of the internal population or more specifically, of the general cruise or ferry passenger demographic.

Given the high values for walking speeds generated by the simplified model, this will result in shorter evacuation times and hence produce a less conservative safety analysis than would be expected if the currently accepted walking speed data-set is used. For this reason, it is suggested that the walking speeds predicted by the simplified model may not be appropriate to use directly within evacuation analysis. However, rather than use the predicted walking speeds directly in evacuation analysis, the model can be used to calculate walking speed reduction factors appropriate for various environmental conditions (heel and Suit type) for each gender and age group. The reduction factor is then applied to the walking speed specified within the IMO evacuation guidelines (Vassalos et al., 2002) to generate the appropriate walking speed for the angle of heel and suit.

The reduction factor (RF) is given by the ratio of the walking speed (WS) predicted by Eq. (5) for the specific condition of age, gender, angle of heel and suit type and dividing it by the predicted WS for the same age and gender for angle of heel 0° and Suit-0:

$$\mathrm{RF}_{\mathrm{age,gender,angle,Suit}}=\frac{\mathrm{Y}_{\mathrm{Age,Gender,Angle,Suit}}}{\mathrm{Y}_{\mathrm{Age,Gender,Angle=0,Suit=0}}}=0.9999^{\mathrm{Angle*Age}}*0.9970^{\mathrm{Angle*Gender}}*0.9934^{\mathrm{Angle*Suit-1}}*0.9363^{\mathrm{Suit-2}}*0.9901^{\mathrm{Angle*Suit-2}} \quad (6)$$

Thus, the walking speed reflecting the impact of the angle of heel and the nature of the suit worn is given by:

$$\mathrm{WS}_{\mathrm{Age,Gender,Angle,Suit}}=\mathrm{WS}_{\mathrm{Age,Gender,Angle=0,Suit=0}}\times\mathrm{RF}_{\mathrm{Age,Gender,Angle,Suit}} \quad (7)$$

where Walking $\mathrm{Speed}_{\mathrm{Age,\ Gender,\ Angle=0,\ Suit=0}}$ is given by the appropriate value from (IMO, 2016). The average reduction factors calculated using Eq. (6) for the identified age ranges, are presented in Table 6 for males and Table 7 for females.

**Table 6**

Reduction factors for mean walking speed for males walking at various angles of heel with various Suit types.

| Suit type | Male group | | | | | |
|---|---|---|---|---|---|---|
| | Age group | Angle of heel | | | | |
| | | 0° | 5° | 10° | 15° | 20° |
| Suit-0 (No Suit) | 18–29 | 1 | 0.986 | 0.972 | 0.958 | 0.945 |
| | 30–50 | 1 | 0.978 | 0.956 | 0.935 | 0.914 |
| | 51–72 | 1 | 0.963 | 0.928 | 0.894 | 0.862 |
| Suit-1 | 18–29 | 1 | 0.954 | 0.910 | 0.868 | 0.828 |
| | 30–50 | 1 | 0.944 | 0.892 | 0.842 | 0.795 |
| | 51–72 | 1 | 0.932 | 0.869 | 0.810 | 0.755 |
| Suit-2 | 18–29 | 0.936 | 0.879 | 0.824 | 0.773 | 0.726 |
| | 30–50 | 0.936 | 0.868 | 0.805 | 0.747 | 0.692 |
| | 51–72 | 0.936 | 0.859 | 0.787 | 0.722 | 0.662 |

**Table 7**

Reduction factors for mean walking speed for females walking at various angles of heel with various Suit types.

| Suit type | Female group | | | | | |
|---|---|---|---|---|---|---|
| | Age group | Angle of heel | | | | |
| | | 0° | 5° | 10° | 15° | 20° |
| Suit-0 (No Suit) | 18–29 | 1 | 0.971 | 0.943 | 0.916 | 0.890 |
| | 30–50 | 1 | 0.963 | 0.928 | 0.894 | 0.861 |
| | 51–72 | 1 | 0.949 | 0.901 | 0.855 | 0.812 |
| Suit-1 | 18–29 | 1 | 0.940 | 0.883 | 0.830 | 0.780 |
| | 30–50 | 1 | 0.930 | 0.866 | 0.805 | 0.749 |
| | 51–72 | 1 | 0.918 | 0.843 | 0.775 | 0.711 |
| Suit-2 | 18–29 | 0.936 | 0.865 | 0.800 | 0.739 | 0.684 |
| | 30–50 | 0.936 | 0.855 | 0.781 | 0.714 | 0.652 |
| | 51–72 | 0.936 | 0.846 | 0.764 | 0.690 | 0.624 |

An important observation concerning the combined impact of wearing TPIS as the angle of heel increases, is that walking speeds can be significantly decreased by the combined impact. The negative effect on walking speeds is not simply a linear combination of both factors. Based on the data presented in Table 6 and Table 7 the following general trends in walking speed reduction are noted:

- The walking speed of females are more severely impacted by heel than males in all age groups for all types of suit.
- The negative impact of heel on walking speeds increases as the angle of heel increases, irrespective of age or gender or suit type.
- At 0° of heel, males and females are equally impacted by wearing Suit-1 and Suit-2.
- At 0° of heel, wearing Suit-1 does not adversely impact walking speeds while wearing Suit-2 results in a 6.4% reduction in walking speed irrespective of age or gender.
- For males aged 18–29, the impact of wearing Suit-2 produces a reduction of 6.4% in walking speed at 0° angle of heel while 20° angle of heel results in 5.5% reduction in walking speed if the same group wear Suit-0. Thus, for this age group wearing Suit-2 has almost similar negative impact on walking speed as a 20° heel while wearing Suit-0. Note that the combined impact of wearing Suit-2 and 20° heel is a 27.4% reduction in walking speed, which is noticeable more than adding each individual impact.
- The negative impact on walking speeds of wearing Suit-1 or Suit-2 at positive (>0°) angle of heel increases with age for both males and females.
- The negative impact on walking speeds of wearing Suit-1 or Suit-2 increases as the angle of heel increases for both males and females.
- The negative impact on walking speeds of Suit-2 is more significant than that of Suit-1 for all angles of heel, across all age groups and genders.
- The most severe reduction in walking speeds occurs at 20° of heel for the oldest age group while wearing Suit-2. This results in walking speeds being reduced by 34% for males and 38% for females.

Currently, the ISO standard suggests TPIS that cause reductions in walking speeds of up to 25% are acceptable (Immersion Suits Test Methods, 2012) . However, it remains to be demonstrated the impact that this type of 'acceptable' reduction in walking speeds will have on evacuation analysis. While considered acceptable from an equipment acceptance criterion, its potential impact on evacuation analysis cannot be ignored and so should be factored into evacuation analysis. It is thus essential to identify the magnitude of walking speed reduction incurred by different types of TPIS. Furthermore, if adverse angles of heel are also considered in the evacuation analysis, this combined with the impact of TPIS can have a severe impact on walking speeds, producing reductions of up to 38% compared to walking speeds without wearing TPIS and at zero angles of heel.

It is noted that the regression model represents the impact of the critical factors on walking speed as a linear function (for example see Fig. 8). However, the trends in the actual data can deviate from linear behaviour, in particular at low angles of heel (see Table 2). This could be due, at least in part, to the low number of participants (and hence data points) in some of the cohorts (see Table 1). Finally, if the log-linear regression analysis is repeated with the previously excluded groups of disqualified participants (see Section 4.1) now included, the identified influencing factors remain significant, albeit with slightly different corresponding coefficients. Furthermore, inclusion of the additional data points reduces the $R^2$ value by 0.04 % points.

## 6. Limitations

As with any experimental study involving human test subjects, there are limitations associated with this work which should be considered when reviewing the results. The limitations of the current study are identified as follows:

- It is acknowledged that this experiment was carried out in a controlled environment in which all possible hazards were mitigated to assure the safety of all participants. This is clearly not the situation that would be experienced in a real-life emergency scenario (on-board a passenger ship). For example, in a real situation the floor surfaces may be wet making them slippery and so increasing the difficulty in walking. However, in order to undertake the research in an ethical manner it was necessary to exclude such factors.
- While angles of heel were incorporated within the experiment, dynamic motion as may be found on-board a vessel was excluded. The inclusion of dynamic motions is left for further research.
- As the trials were conducted by a single participant at a time, the impact of group behaviours or contra-flows were not considered. This research focused on the collection of unimpeded walking speed data similar to that currently used in evacuation analysis. Thus, the impact of groups behaviours, while of importance, was considered beyond the scope of the current project and is left for further research.
- The sequence of walking through the corridor at two angles (0° and heeled case) should ideally have been randomised for each participant. However, this was impractical due to the time required to change the angle of heel. Therefore, all participants consistently walked first through one angle of heel and subsequently 0° of heel.
- All participants walked through the corridor with it heeled towards their left. It is possible that walking performance could be influenced by the handedness of the participant. As this was not explored in these trials, this aspect is left for further research.
- The trial participants were all fit and healthy with many undertaking regular exercise two to five times per week. Within the experimental population, just 9% of the participants had BMI greater than 30 which is classified as obese. It is noted that in the UK and USA 27% and 38%, respectively of the population are classified as obese (Gallagher et al., 2000). Thus, the sample population used in the trials may not be considered fully representative of the target population. While further research is required to include a wider cross-section of the public, the walking speeds measured in these trials may be considered to be representative of upper limits. Furthermore, in order to be conservative, the reduction factors suggested in this paper should be considered as minimum values until further research can be undertaken.
- Only two types of protective suit were assessed. However, the results suggest that the design of protective clothing can have a significant impact on walking performance. Hence, it is essential that each unique concept in protective clothing is assessed for its impact on walking performance.

## 7. Conclusion

The safe evacuation of passenger ships is always challenging, particularly in arctic regions where extreme cold requires passengers to wear TPIS prior to abandoning the vessel. While the primary requirement is that the survival suit must provide thermal protection, it is also essential that it does not impede evacuation. To be considered appropriate for use, including cold conditions, the ISO standard requires that the wearing of TPIS must not reduce average walking speed by more than 25%. Compliance with this requirement is demonstrated by determining the average walking speed produced by only six individuals wearing the TPIS and walking over 30 m under conditions of 0° of heel. Currently, the acceptance requirements do not consider age or angle of heel as potentially important factors in influencing walking speeds and so these factors are ignored in the acceptance requirements.

To assess the impact of these variables on walking speeds, a unique study was undertaken that involved the development of a 36 m long test facility resembling a ships corridor. The facility could be orientated to four different angles of heel (0°, 10°, 15°, and 20°) enabling walking speeds to be evaluated for each orientation. In total walking speeds from 210 participants (males and females) ranging in age from 18 to 72 years were collected. Participants were instructed to walk through the corridor twice, first at 10°, 15° or 20° of heel and then at 0° of heel. Participants wore either normal clothing or one of two types of survival suit, Suit-1 or Suit-2, with Suit-2 being heavier and bulkier than Suit-1.

Results of the analysis demonstrate that gender, age, height, weight, angle of heel and the nature of the survival suit significantly influenced walking speed. For comparison purposes, the impact of heel and suit type on walking speed is assessed by comparison to the walking speed at 0° of heel while wearing normal clothing.

The analysis suggests that males consistently walked faster, on average, than females within all age groups and under all conditions. However, at 0° of heel, the reduction in average walking speed due to wearing the survival suit (i.e. Suit-1 or Suit-2) was the same for males and females and independent of age group. For Suit-1 there was no reduction in average walking speed, while for Suit-2, the average reduction in walking speed was 6.4%. Furthermore, at all other angles of heel and for all clothing states, the reduction in average walking speeds for females was greater than that for males and the reduction in walking speeds increased with age. The most significant reduction in walking speeds occurred at 20° of heel for Suit-2, resulting in a 38% reduction for the female 51–72-year age group while the corresponding reduction for Suit-1 was 29%. The reduction in walking speeds due to wearing protective clothing becomes more severe as the angle of heel increases and is clearly dependent on the nature of the protective clothing, with reductions due to Suit-2 being greater than Suit-1.

As reductions in walking speed due to the nature of the survival suit and the angle of heel can be significant, it is important to take these factors into consideration when undertaking evacuation analysis. For the two types of survival suit examined in this study, a method for calculating the appropriate reduction in walking speed as a function of age, gender, angle of heel and survival suit type has been provided.

As only two types of survival suit were assessed in this study and the results produced by both differed considerably, it is suggested that suit specific walking speed reduction factors should be specified by suit manufacturers. If walking speed reduction factors for a specific suit are not available, it is suggested that the most severe reduction factors provided in this study should be utilised in evacuation analysis.

### *CRediT authorship contribution statement*

**Hooshyar Azizpour:** Investigation, Methodology, Formal Analysis, Writing – original draft, Writing – review & editing, Resources. **Edwin R. Galea:** Investigation, Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Formal analysis. **Sveinung Erland:** Formal analysis, Supervision, Writing – review & editing. **Bjørn-Morten Batalden:** Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Steven Deere:** Investigation, Formal analysis, Methodology. **Helle Oltedal:** Investigation, Funding acquisition, Project administration, Supervision, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgement

The authors would like to express their deepest appreciation to all those who contributed to this study. This work could never have been accomplished without the financial support from MARKOM-2020 (T92). Special thanks also goes to Viking Life-Saving Equipment and Hansen Protection for providing the TIPS(s) used in the study. Further, we acknowledge with great appreciation, the invaluable support of the ARCOS and ResQ safety centres for providing access to invaluable facilities to conduct the experiments and to the staff of UiT and HVL who assisted with the safe and efficient running of the experiments. Finally, we are indebted to the 210 volunteers who freely gave their time to improve maritime safety.

## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssci.2021.105621.

## References

Aghabayk, K., Parishad, N., Shiwakoti, N., 2021. Investigation on the impact of walkways slope and pedestrians physical characteristics on pedestrians normal walking and jogging speeds. Safe. Sci. 133, 105012.

Benoit, K., 2011. Linear regression models with logarithmic transformations. Lond. School Econ. Lond. 22 (1), 23–36.

Bles, W., Nooij, S., Boer, L., Sharma, S.S., 2002. Influence of ship listing and ship motion on walking speed. In: International Conference on Pedestrian and Evacuation Dynamics 2001. Springer, pp. 437–452. [Online]. Available: http://pubman.mpdl.mpg.de/pubman/faces/viewItemOverviewPage.jsp?itemId=escidoc:1793005.

Boyce, K.E., Shields, T.J., Silcock, G.W.H., 1999. Toward the characterization of building occupancies for fire safety engineering: capabilities of disabled people moving horizontally and on an incline. Fire Technol. 35 (1), 51–67. https://doi.org/10.1023/a:1015339216366.

Brumley, A., Koss, L., 2000. The influence of human factors on the motor ability of passengers during the evacuation of ferries and cruise ships. Conference on Human Factors in Ship Design and Operation.

Chang, W.-R., Matz, S., Chang, C.-C., 2012. A comparison of required coefficient of friction for both feet in level walking. Safe. Sci. 50 (2), 240–243.

Chang, W.-R., Matz, S., Chang, C.-C., 2013. The available coefficient of friction associated with different slip probabilities for level straight walking. Safe. Sci. 58, 49–52.

Cooper, G.F., Herskovits, E., 1991. A Bayesian method for constructing Bayesian belief networks from databases. In: Uncertainty Proceedings 1991. Elsevier, pp. 86–94.

Fruin, J.J., 1971. Pedestrian planning and design, Metropolitan association of urban designers and environmental planners. Inc., New York.

Galea, E., 2000. Safer by design: Using computer simulation to predict the evacuation performance of passenger ships. In: Safety of Large Passenger Ships - Looking to the Future. Conference Proceedings. IMarE Conference, 112 (2). The Institute of Marine Engineers, London, UK, pp. 7-16. ISBN 1902536304. [Online]. Available: http://gala.gre.ac.uk/id/eprint/386.

Galea, E., Owen, M., 1994. Predicting the evacuation performance of mass transport vehicles using computer models. [Online]. Available: https://trid.trb.org/view/449582.

Galea, E., Deere, S., Brown, R., Filippidis, L., 2013. Two evacuation model validation data-sets for large passenger ships, SNAME (The Society of Naval Architects and Marine Engineers). J. Ship Res. 57 (3), 155–170.

Galea, E., Filippidis, L., Gwynne, S., Lawrence, P., Sharp, G., Blackshields, D., Glen, I., 2002. “The development of an advanced ship evacuation simulation software product and associated large scale testing facility for the collection of human shipboard behaviour data”. In: RINA. International Conference. Human Factors in Ship Design and Operation, 2-3 October 2002. Papers. The Royal Institution of Naval Architects, London, UK, pp. 37-50. ISBN 9780903055819 [Online]. Available: http://gala.gre.ac.uk/id/eprint/557.

Galea, E., 2003. MaritimeEXODUS V4. 0: User Guide and Technical Manual. CMS Press.

Gallagher, D., Heymsfield, S.B., Heo, M., Jebb, S.A., Murgatroyd, P.R., Sakamoto, Y., 2000. Healthy percentage body fat ranges: an approach for developing guidelines based on body mass index. Am. J. Clin. Nutrit. 72 (3), 694–701.

Glen, I.F., Igloliorte, G., Galea, E.R., Gautier, C., 2003. Experimental determination of passenger behaviour in ship evacuations in support of advanced evacuation simulation. In: International Conference on Passenger Ship Safety, London. Royal Institution of Naval Architects (RINA), pp. 129–138. [Online]. Available: https://pdfs.semanticscholar.org/e774/893afca220ba09df9c3e8ef06d8277b2c540.pdf.

Gwynne, S., Galea, E., Lyster, C., Glen, I., 2003. Analysing the evacuation procedures employed on a Thames passenger boat using the maritimeEXODUS evacuation model. Fire Technol. 39 (3), 225–246.

Heliövaara, S., Kuusinen, J.-M., Rinne, T., Korhonen, T., Ehtamo, H., 2012. Pedestrian behavior and exit selection in evacuation of a corridor – an experimental study. Safe. Sci. 50 (2), 221–227.

Hwang, K., Chung, D., Lee, D., 1991. An analysis of gait characteristic parameters for the Korean normal adults. J. Human Eng. Soc. Korea 10 (2), 15–22.

Immersion Suits Test Methods, 2012. ISO-15027-3, Page 11.

IMO SOLAS, 2004. Chapter III/3, No. 1341, Life Saving Appliences, S. IMO, 11 October 2004.

IMO, 2002. MSC/Circ. 1033. Interim Guidelines for Evacuation Analyses for New and Existing Passenger Ships, 2002.

Regulations of 1 July 2014 on life-saving appliances on ships, Circular – Series R S. IMO, 01.07.2014, 2014.

IMO, 2016. MSC/Circ. 1533, Revised guidelines on evacuation analysis for new and existing passenger ships, London, 6 June 2016.

International Maritime Organization [IMO], 2017. International Code for Ships Operating in Polar Waters (Polar Code) (MEPC 68/21).

IMO-SOLAS, 1998. Revised recommendations on testing of Life-Saving Appliences, ANNEX 6, Resolution MSC.81(70)- MSC 70/23/Add.1, IMO-SOLAS.

Inoue, W., Ikezoe, T., Tsuboyama, T., Sato, I., Malinowska, K.B., Kawaguchi, T., Tabara, Y., Nakayama, T., Matsuda, F., Ichihashi, N., 2017. Are there different factors affecting walking speed and gait cycle variability between men and women in community-dwelling older adults? Aging Clin. Exp. Res. 29 (2), 215–221.

Kim, K., Steinfeld, E., 2019. The effects of glass stairways on stair users: an observational study of stairway safety. Safe. Sci. 113, 30–36.

Kong, P.W., Suyama, J., Hostler, D., 2013. A review of risk factors of accidental slips, trips, and falls among firefighters. Safe. Sci. 60, 203–209.

Koss, L., Moore, A., Porteous, B., 1997. Human mobility data for movement on ships. In: Presented at the International Conference on Fire at Sea, UK. [Online]. Available: https://research.monash.edu/en/publications/human-mobility-data-for-movement-on-ships.

Kruke, B.I., 2021. Survival through coping strategies for resilience following a ship accident in polar waters. Safe. Sci. 135, 105105.

Kruke, B.I., Auestad, A.C., 2021. Emergency preparedness and rescue in Arctic waters. Safe. Sci. 136, 105163.

Lee, D., Park, J.-H., Kim, H., 2004. A study on experiment of human behavior for evacuation simulation. Ocean Eng. 31 (8), 931–941. https://doi.org/10.1016/j.oceaneng.2003.12.003.

Lei, W., Tai, C., 2019. Effect of different staircase and exit layouts on occupant evacuation. Safe. Sci. 118, 258–263.

Luck, M., Maher, P.T., Stewart, E.J., 2010. Cruise Tourism in Polar Regions: Promoting Environmental and Social Sustainability? Routledge.

Nicholls, I., Hifi, Y., Lee, B.S., Galea, E.R., Deere, S., Blackshields, B., Sharp, G., Safeguard Passenger Evacuation Seminar, 30, November 2012, London. T. R. I. o. N. Architects. The SAFEGUARD heel scenario evacuation benchmark and recommendations to IMO to update MSC Circ 1238. Available: https://fseg.gre.ac.uk/fire/12_84.pdf.

Park, K., Rosengren, K.S., Horn, G.P., Smith, D.L., Hsiao-Wecksler, E.T., 2011. Assessing gait changes in firefighters due to fatigue and protective clothing. Safe. Sci. 49 (5), 719–726.

Pradillon, J. 2004. ODIGO-modelling and simulating crowd movement onboard ships. In: 3rd International Conference on Computer and IT Applications in the Maritime Industries, COMPIT, Siguenza, Spain, pp. 278–289.

Predtechenskii, V.M., Milinskiĭ, A.I., 1978. Planning for Foot Traffic Flow in Buildings. National Bureau of Standards, US Department of Commerce, and the National Science Foundation, Washington, DC.

Rawlings, J.O., Pantula, S.G., Dickey, D.A., 2001. Applied Regression Analysis: A Research Tool. Springer Science & Business Media.

Shiwakoti, N., Shi, X., Ye, Z., 2019. A review on the performance of an obstacle near an exit on pedestrian crowd evacuation. Safe. Sci. 113, 54–67.

Sun, J., Guo, Y., Li, C., Lo, S., Lu, S., 2018. An experimental study on individual walking speed during ship evacuation with the combined effect of heeling and trim. Ocean Eng. 166, 396–403. https://doi.org/10.1016/j.oceaneng.2017.10.008.

Vassalos, D., Kim, H., Christiansen, G., Majumder, J., 2002. A mesoscopic model for passenger evacuation in a virtual ship-sea environment and performance-based evaluation.

Wang, X., Liu, Z., Wang, J., Loughney, S., Yang, Z., Gao, X., 2021. Experimental study on individual walking speed during emergency evacuation with the influence of ship motion. Physica A: Stat. Mech. Appl. 562, 125369.