Fire Technology
https://doi.org/10.1007/s10694-025-01731-z

Decoding Hospital Evacuation Drills: Pre-movement and Movement Analysis in New Zealand

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Received: 4 September 2024 / Accepted: 12 March 2025

Abstract
Hospital evacuations present unique challenges due to the dependency of patients on medical staff and specialized equipment, making the process particularly complex. This study investigates the pre-movement and movement phases during hospital evacuation drills conducted in New Zealand, providing rare and valuable data that are critical for improving evacuation modeling in healthcare settings. Eight evacuation drills were conducted across various hospital units, including General Ward (GW) spaces, a Hyper Acute Stroke Unit (HASU), a High Dependency Unit (HDU), and a Post-Anesthesia Care Unit (PACU), with detailed documentation and analysis of preparation times, pre-movement times, and evacuation speeds. The results reveal significant variability in pre-movement times, heavily influenced by the specific needs of different units and the evacuation methods employed (e.g., beds, wheelchairs, walking). High-acuity units like the HDU, where patients require extensive medical support, exhibited notably longer active preparation times due to the complexity of disconnecting medical equipment. Additionally, horizontal movement speeds were slower for patients evacuated on beds compared to those using wheelchairs or walking. Given the rarity of such data and the uncertainty about the applicability of findings from other building types, this study underscores the need for tailored evacuation strategies that consider the distinct requirements of hospital environments. The findings highlight the importance of accounting for the dependencies on medical personnel and equipment, contributing to more accurate and effective evacuation planning in healthcare facilities. Further, the findings highlight the nuanced behaviours observed during healthcare evacuations, and provide valuable inputs for fire and evacuation modellers when designing for healthcare occupancies.

Keywords Hospital evacuation · Pre-movement · Speed · Egress modelling input · Evacuation drill

Abbreviations

GW	General ward
HASU	Hyper acute stroke unit
HDU	High dependency unit

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Published online: 24 April 2025

ICU Intensive care unit
PACU Post-anesthesia care unit

1 Introduction

Fire and evacuation modelling tools are becoming increasingly popular in fire engineering to carry out performance-based assessments of the built environment. The latest survey on the use of computer-based evacuation modeling tools shows that users can choose among over 70 options [1]. Notwithstanding the availability of simulation tools, one of the main challenges for fire engineers is the selection of appropriate input values. These input values are fundamental to defining the pre-evacuation and movement behaviors of the simulated evacuees and can significantly impact the final output of the model [2–4]. The selection of reasonable values is one of the most important tasks while using existing models. Fire engineers are required to make reasonable assumptions and to identify suitable values from existing behavioral studies or reports. As such, evacuation databases represent one of the most useful tools to support fire engineering practitioners in this challenging task.

The pioneering work of Fahy and Proulx [5] provides the first instance of an evacuation database in the fire engineering field. In fact, they acknowledged and foresaw the need for lists of existing evacuation studies providing quantitative data on pre-evacuation times, walking speeds, and evacuees' characteristics and actions. As such, Fahy and Proulx established a strategic pathway for the field. Today, many new evacuation studies have been published, providing new evacuation data that is usable to improve assumptions on evacuation simulations. Following the pathway of Fahy and Proulx [5], new databases have been proposed in the last 20 years by Shi et al. [6], Gwynne and Boyce [7], Geoerg et al. [8] and Lovreglio et al. [9]. Although these databases aim to provide a comprehensive overview of all the types of occupancy, there is still a clear gap on some specific types of occupancies requiring assisted evacuation, such as hospitals, healthcare facilities, and retirement homes. A partial answer to this need is the database by Geoerg et al. [8] who provide data focusing on evacuees with reduced mobilities. However, this work does not include a comprehensive analysis of hospital evacuations.

Simulating hospital evacuation is still a major challenge. This task can be done assuming both a total and staged evacuation depending on the fire safety strategy and building design aspects (e.g., fire compartments, fire safety systems, and evacuation zones). Today, different evacuation tools have been adapted to simulate assisted evacuations for hospitals [10–12]. Most of these tools allow engineers to simulate hospital staff to assist patients with mobility impairments evacuating them using different devices such as beds, chairs, or other specialized devices [12]. In this type of simulation, fire engineers are often asked to make sensitive choices when setting up the hospital simulations. However, this task is still very challenging given the lack of an evacuation database on preparation times and evacuation speeds using hospital evacuation equipment. This is also partially due to the lack of existing data from hospital evacuations.

This work aims to provide new instruments for fire engineers to perform reliable evacuation simulations for hospitals. To achieve this target, we provide new evacuation data collected from eight evacuation exercises carried out in two hospitals in New Zealand. These exercises were video recorded by the research team and the video footage was analyzed to generate new data on assisted evacuation times and speeds in hospitals.

Further, we generate a new database combining this new data on preparation times, pre-movement times, and evacuation speeds with the existing data from the existing evacuation literature.

2 (Data) Background

Figure 10 summarises the pre-movement times observed in various empirical studies related to healthcare facilities. Generally, most studies report pre-movement times within a similar range of approximately 50–300 s. Additionally, the study by Gwynne et al. [13] highlights significant differences in pre-movement times between a hospital outpatient area and a university library, emphasizing the dependency on staff instructions, which can delay evacuation initiation in hospitals.

This indicates a general consistency in response times across different healthcare settings and populations. However, it is noteworthy that some drills exhibit outliers and extremes, as reported by Schliephake [14] and Kuligowski et al. [15], showing significantly higher pre-movement times extending beyond 500 s. These observations suggest the presence of unobserved heterogeneity, such as the influence of specific population characteristics or the boundaries of facilities, resulting in prolonged initiation of the evacuation process.

Focusing on healthcare facilities, three general findings are striking:

Existing pre-movement data on evacuation in healthcare facilities are mainly limited to outpatients facilities [2, 13, 16, 17]. There is a lack of data that considers the specific challenges associated with hospital evacuations. The importance of staff training is highlighted by Strating [18], who reports that well-trained staff can significantly improve evacuation efficiency, especially in the context of bedridden patient evacuation.

The influence of mobility attributes and assistive devices on the evacuation process is notable. Studies by Hoondert [19] and Kuligowski et al. [15] indicate extended pre-movement times for populations requiring assistance. Schliephake [14] reports that individuals with disabilities generally have longer pre-movement times due to the need for assistance or physical limitations. Consistently, studies show that pre-movement times are heavily influenced by occupant characteristics such as age, physical and mental disabilities, and familiarity with the environment.

A significant difference is observed between bedridden patients and those who are ambulatory. Bedridden patients tend to have higher pre-movement times, as seen in studies by Hoondert [19] and Hunt et al. [20].

The data on the movement speeds of evacuees in healthcare contexts highlights significant variability, which is largely influenced by the type of assistive devices used, the physical capabilities of the individuals, and the specific evacuation scenarios (cf. Figure 11 for comparison). On average, movement speeds range from approximately 0.04 to 1.54 $m\,s^{-1}$.

Individuals with higher mobility levels or those using advanced assistive devices exhibit faster movement speeds. For example, Geoerg et al. [21] found that participants without disabilities demonstrated lower movement times (resulting in higher speeds) compared to those with disabilities; the level of assistance required also impacted movement speeds. In the study by Hunt et al. [20], devices requiring less manual effort from handlers (e.g., evacuation chairs) allowed for quicker movement compared to those requiring significant physical exertion (e.g., stretchers and rescue sheets).

The effectiveness of evacuation is enhanced with trained staff, as highlighted by Strating [18]. Hunt et al. [20] emphasized that trained hospital staff using evacuation chairs achieved consistent and efficient speeds, demonstrating the importance of regular training and drills. Unannounced drills, as conducted by Geoerg et al. [21], revealed higher variability in movement speeds, which can be attributed to the element of surprise and the real-time decision-making required during such evacuations.

Our study aims to bridge these gaps by focusing specifically on hospitals rather than general healthcare facilities. We emphasize the importance of conducting research under 'realistic' conditions in natural environments, using actual hospital staff instead of actors.

Additionally, it is crucial to consider the different occupancy types within a hospital to gain a comprehensive understanding of evacuation dynamics. Previous studies suggest that various assistive devices, such as wheelchairs, beds, and other mobility aids, significantly influence evacuation outcomes. However, these factors have not been adequately explored. By including these elements in our investigation, we aim to accurately reflect the diverse needs and challenges of hospital evacuations.

3 Methods

In 2020 a series of eight announced evacuation drills were conducted across two hospitals in New Zealand (Hospital A and Hospital B).

The evacuation drills were carried out across several occupancy types within the hospitals.

3.1 Case Studies

Evacuation Drills 1A and 1B were carried out at a post-anesthesia care unit (PACU) within Hospital A on 18 September 2020 at approximately 08:00 h. The evacuation drill was repeated twice (hence the naming convention 1A and 1B). Each of the PACU drills contained simulated patients occupying eight beds and four chairs. Drills 1A and 1B had eight staff available for each drill.

Evacuation Drill 2 was carried out at a Hyper Acute Stroke Unit (HASU) within Hospital B on 09 November 2020 at approximately 15:00 h. Drill 2 contained simulated patients occupying eleven beds and was conducted with six nurses on staff which was intended to simulate night-time staffing levels.

Evacuation Drill 3 was carried out at a General Ward (GW) space within Hospital B on 09 November 2020 at approximately 14:00 h. This drill contained simulated patients occupying eight beds and three chairs. There were thirteen staff available for Drill 3.

Evacuation Drills 4A and 4B comprise two repetitions of evacuation drills in a GW space at Hospital A on 14 December 2020 at approximately 06:30 h. This drill contained simulated patients occupying three beds. Ten staff were available for Drill 4A and eleven for Drill 4B.

Evacuation Drills 5A and 5B comprise two repetitions of evacuation drills of two negative pressure isolation rooms in a High Dependency Unit (HDU) at Hospital A on 09 November 2020 at approximately 20:00 h. Each isolation room contained a single simulated patient in a bed. Twelve staff were available for Drill 5A and eleven for Drill 5B.

Table 1 Descriptive data for hospital evacuation drills; Drill No.s with an A or B suffix indicate a repetition of the same base scenario

Drill no.	Date	Location	Occupancy type	Patients [movement devices]	Staff
1A	18 Sep 2020	Hospital A	PACU	8 [bed], 4 [wheelchair]	8
1B	18 Sep 2020	Hospital A	PACU	8 [bed], 4 [wheelchair]	8
2	09 Nov 2020	Hospital B	HASU	8 [bed], 2 [wheelchair]	6
3	09 Nov 2020	Hospital B	GW	3 [bed], 5 [wheelchair], 3 [walking]	13
4A	14 Dec 2020	Hospital A	GW	3 [bed]	10
4B	14 Dec 2020	Hospital A	GW	3 [bed]	11
5A	09 Nov 2020	Hospital A	HDU—Isolation rooms	2 [bed]	12
5B	09 Nov 2020	Hospital A	HDU—Isolation rooms	2 [bed]	11

Occupancy types are defined as follows: General Ward (GW), Hyper Acute Stroke Unit (HASU), High Dependency Unit (HDU), Post-Anesthesia Care Unit (PACU)

A summary of case study data is available in Table 1. Figure 13 in App C presents detailed sketches/floorplans for better orientation.

3.2 Materials

Cameras were installed in multiple locations for each of the drills. The cameras used were two DSLR cameras, and up to eight Mini Wifi HD cameras within each of the evacuation zones. Staff were made aware of the presence of cameras but apart from the two DSLR cameras the remaining Nextech 1080p Miniature DV cameras were installed on walls above head height and were relatively unobtrusive.

See Figures at Appendix C for camera locations and starting locations of all patients.

3.3 Exercise Conditions

The studies described in this paper were carried out in conjunction with an evacuation consultant as part of each hospital's mandated twice-yearly evacuation drills. For each of the drills the evacuation consultant delivered a pre-briefing to staff to advise them of the process, this was also used as an opportunity for staff training to familiarise themselves with their required actions during an emergency evacuation. After this pre-briefing the fire alarm was activated by one of two methods, either by activating a smoke detector (by smoke pen or smoke detector testing aerosol) or by advising staff that there was a fire and directing them to activate a manual call point.

After alarm activation, there was no further involvement from the evacuation consultants and staff carried out their normal evacuation actions until all patients were evacuated from the area.

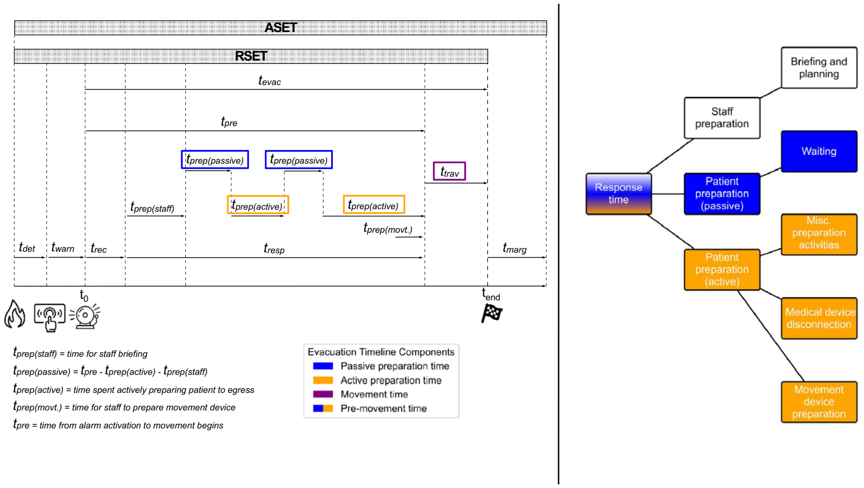


Fig. 1 Evacuation timeline (left): The observed components of the evacuation timeline are overlaid on the well-established RSET timeline as described in Gwynne and Boyce [7, p. 2434]. Time t_0 is the point at which alerting devices are activated, and time t_{end} is taken when the patients pass through the exit doors of their initial compartment. After $t_{prep(staff)}$ is completed, staff activity time components switch between $t_{prep(active)}$ and $t_{prep(passive)}$ depending on the waiting time required for additional staff or equipment. Observed sub-components of pre-movement response time (right): the actions observed during the pre-movement times were characterised by different activity levels (active/passive)

3.4 Data Collection and Analysis Methods

Recorded video footage for each of the drills was reviewed to identify key elements and their timings within the evacuation process. During this preliminary analysis, several distinct sub-components were observed during the pre-movement time. These included components such as staff briefing activities, movement of staff around patients, passive periods where patients were waiting for something (either portable medical equipment, or additional staff to assist with their egress), and active periods where staff were preparing patients for egress. In order to measure these aspects consistently and accurately, it was necessary to operationalise these components.

3.4.1 Coding of Observations

For transparency, the operationalisation of these aspects is broken down into the following components (see Fig. 1)

- Pre-movement time, t_{pre} - The total period between alarm activation and purposeful movement of a patient toward the exit.
- Staff preparation, $t_{prep(staff)}$ - The portion of pre-movement time, where staff are either seeking further information or conducting briefing and planning activities before any purposeful patient preparation phases of evacuation are carried out.
- Preparation time (passive), $t_{prep(passive)}$ - The portion of pre-movement time when patients are not actively being 'worked on' toward an effort for evacuation. Examples of

this are waiting time for equipment to arrive (such as portable oxygen), or waiting time for staff to arrive (where there are staff-patient ratios of less than 1:1).

- Preparation time (active), $t_{prep(active)}$ - The portion of pre-movement time that is associated with staff members actively getting a patient ready for evacuation. This includes movement device preparation time, medical device disconnection time, and miscellaneous preparation activities such as briefing the patient about the evacuation.
  - Movement-device preparation time, $t_{prep(movt.)}$ - The portion of preparation time (active) that is solely associated with actively preparing the movement device for egress. For a wheelchair, this time begins when the wheelchair is positioned beside the patient, including transit time to situate the patient in the wheelchair, and the time ends when the device is in a configuration that is ready for movement. For a bed this time is considered when staff are directing actions toward activities such as unplugging the bed power supply, raising the side barriers, and releasing the brakes, and this time is considered to end when the device is in a configuration that is ready for movement.
  - Medical device disconnection time, $t_{prep(disc.)}$ - The portion of preparation time (active) that is associated with the disconnection of medical equipment to prepare a patient for evacuation.
  - Miscellaneous preparation activities, $t_{prep(misc.)}$ - The portion of preparation time (active) that is associated with staff communicating with patients about the evacuation.

Using the operational parameters identified above, each of the drills was analysed and timings were entered for each observable sub-component on a patient by patient basis into a combined spreadsheet to enable further analysis. As detailed in Fig. 1, it is important to note that for some patients there was a switching between active and passive phases of preparation, this would occur for example when there was one staff member responsible for preparing two patients for egress, often the staff member would alternate between the two, rather than sequentially preparing each patient.

4 Results

This section describes the results obtained from the evacuation drills, beginning with qualitative observations before exploring the quantitative results.

4.1 General Observations

A summary of the evacuation timeline from alarm activation to the end of the movement phase is presented in Fig. 2, where each patient's egress time components are broken down for comparison. It consists of *passive* and *active* preparation time (which is the pre-movement time) and the travel time (movement time). Within Fig. 2, there is noticeable variability in the evacuation times across different drills and modalities (bed, chair, walking).

As discussed in Sect. 3.4.1, in some cases, staff alternated between active and passive preparation phases, this was mostly evident in the PACU area. In many cases, these phases

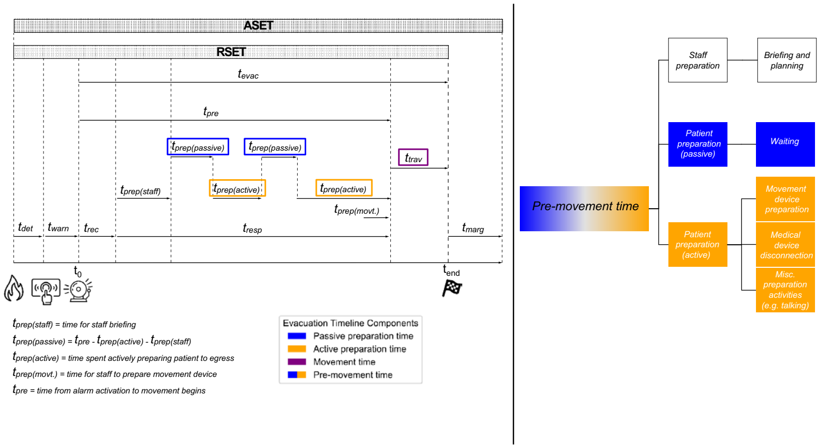


Fig. 2 Timeline separated by time components for pre-movement and movement phase for each unique device in each type of occupancy [General Ward (GW), Hyper Acute Stroke Unit (HASU), High Dependency Unit (HDU), Post-Anesthesia Care Unit (PACU)]. The pre-movement time presented here consists of *active* and *passive* preparation time. Annotated is the movement phase as a percentage of the overall evacuation time. Please note the one case (Drill 5A–Bed2), where a negative *active* preparation time is presented. In this case, staff began preparation before the alarm alerting devices had activated, hence the negative value. The reason for this was the 'group leader' had activated the manual call point and then immediately given staff the order to evacuate, this instruction occurred before the alerting devices activated, which was shortly after. It was also noted in these specific wards, the isolation rooms appear very well insulated (acoustically), and the alarm could not be heard by staff in these areas, as evidenced by staff comments observed in the videos. The first these staff knew of an evacuation was when the 'group leader' came in to tell them the alarm had gone off, and they needed to start evacuating

alternated between two and four times and in one case five times. There were two causes observed for this splitting of activity; (1) where one staff member was responsible for more than one patient (in this case, they would often switch between patients, rather than preparing each patient fully for egress sequentially), or (2) where there were long waiting times for equipment (in which case a staff member would do a little preparation, wait, do a little more preparation, wait, etc...).

In some drills, there were many 'observers', i.e., people in the area who were present but not involved in the evacuation activities. This made the data collection of staff activities challenging, as often the observers were dressed in the same uniform as the participating staff members. Clear demarcation of participants and observers would have been useful.

While there were attempts in some drills to add detail to the scenarios (such as A4 pages of paper attached to 'patients' with medical conditions, history, and equipment), in almost all cases this was observed to be ignored by staff during the evacuation drills and there was no real consideration of any patients scripted specific medical conditions and equipment.

There was limited urgency observed by some of the staff and patients participating in the drills. Examples of this were staff disconnecting monitor leads from patients and taking time to calmly re-coil these leads and tidily place them back on the monitor. While this aligns partially with some human behaviour theories such as the role-rule model and affiliation type behaviours, in reality, we expect these would be left alone while patient egress was prioritised. Other examples were staff and patients joking and laughing together as they were waiting or during their egress travel.

In the HDU isolation rooms (Drills 5A and 5B), the level of acoustic insulation was such that the fire alarm alerting devices could not be heard by staff in these spaces. For these spaces, the cues provided to staff members were via the team leader opening the door and explaining to them a fire evacuation was occurring, and instructing them to prepare their patient for immediate movement.

With reference to Fig. 2, the average ratio of the movement time in the total evacuation time is $\approx 27 \pm 14\,\%$. The range extends from 4 % to 53 %. There appears to be no clear association with the mode of evacuation (bed, walking, wheelchair), indicating other factors that can better explain the differences in preparation time ratios. A substantial average share of $51 \pm 24\,\%$ of the *passive* preparation time in the total evacuation time is striking, while the *active* component of the preparation time is on average $18 \pm 13\,\%$, (please note that the data from Trials 5A and 5B were excluded for the calculation of the share of components, as they contain an over-proportionate share of the active phase).

4.2 Active Preparation Time

The active component of the preparation time is illustrated in Fig. 3. Unlike the timeline presented in Fig. 2, the data points here are organized by the type of area and the evacuation mode. On average, the staff required 51.8 ± 91.4 s to prepare for the movement phase, with the preparation times ranging from 1.0 to 520 s. When excluding the High Dependency Unit (HDU) from the analysis, the average active preparation time is significantly reduced to 29.0 ± 24.6 s.

The concentration of values at the high end of the distribution in the HDU unit (see aggregated means for HDU-Bed in Fig. 4) suggests a systematic peculiarity in this unit. The reason for the high active preparation time in the HDU area was primarily due to the higher level of acuity of the simulated patient with more connected medical devices. Disconnecting this equipment and preparing the patient to move took longer than the other types of areas where there was a lower patient acuity and consequently fewer medical devices that required disconnection.

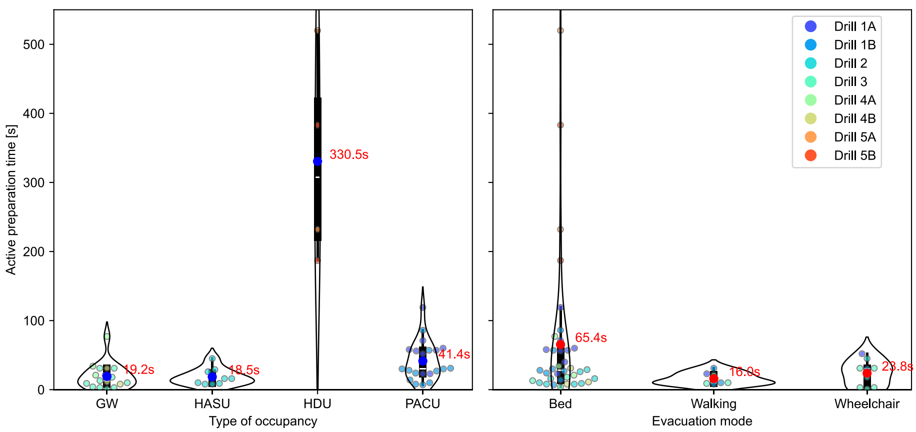


Fig. 3 Active preparation time by type of occupancy [General Ward (GW), Hyper Acute Stroke Unit (HASU), High Dependency Unit (HDU), Post-Anesthesia Care Unit (PACU)], evacuation mode, and exercise

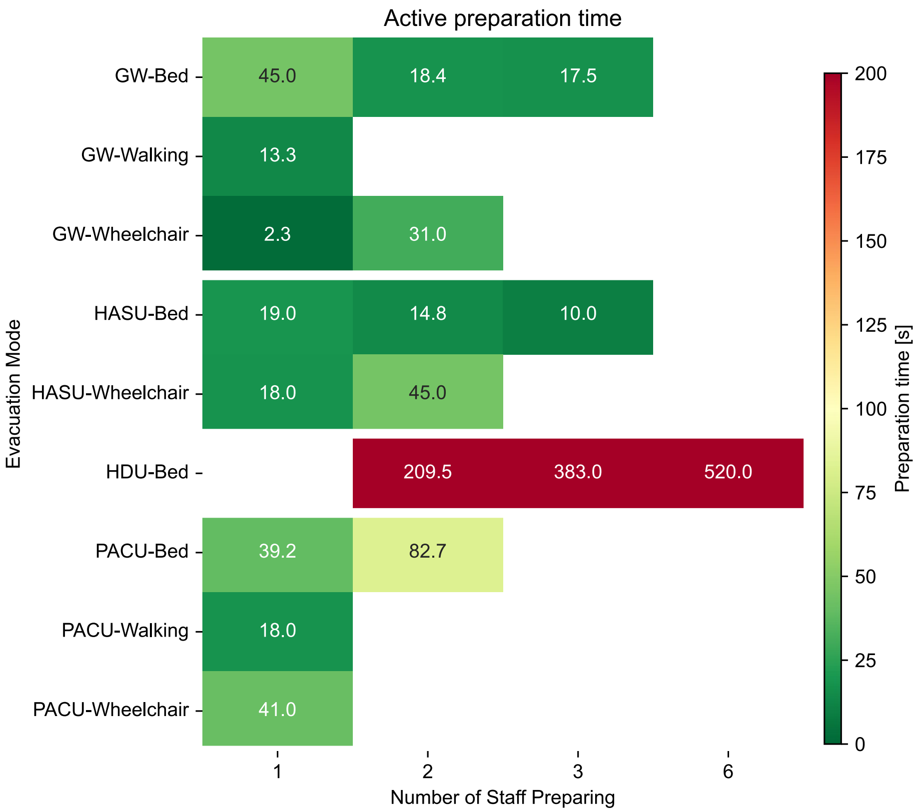


Fig. 4 Average active preparation time compared to the evacuation mode and the number of staff assisted in preparation actions in each type of occupancy [General Ward (GW), Hyper Acute Stroke Unit (HASU), High Dependency Unit (HDU), Post-Anesthesia Care Unit (PACU)]

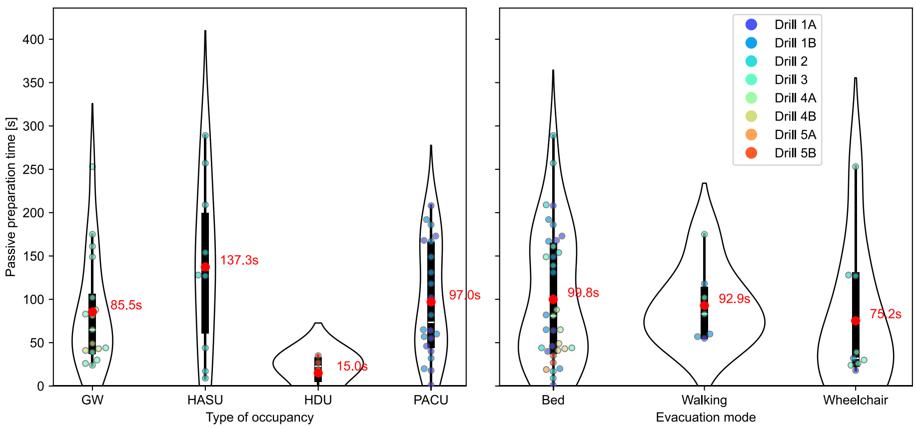


Fig. 5 Passive preparation time by type of occupancy [General Ward (GW), Hyper Acute Stroke Unit (HASU), High Dependency Unit (HDU), Post-Anesthesia Care Unit (PACU)], evacuation mode, and exercise

Analyzing the three evacuation modes, it is evident that the use of a bed results in the longest preparation time, averaging 65.4 ± 106.5 s (without HDU: 33.2 ± 27.2 s), with a range from 4.0 to 520.0 s. In contrast, the average active preparation times for the Walking (16.0 ± 9.0 s) and Wheelchair (23.8 ± 18.7 s) modes are relatively similar. Excluding the HDU unit does not affect these values, as only beds were utilized in the HDU.

4.3 Passive Preparation Time

Figure 5 depicts the time that is not actively used for preparing actions or introducing staff. It is presented as grouped by type of area and modes of movement. While the mean values for the types of area GW, HSU, and PACU are within a comparable range between 85.5 and 97.0 s, and the standard deviations are also comparable (64.2–95.8 s), the values for the HDU are noticeably different: 15.0 ± 24.9 s.

The direct comparison of the movement modes shows no noticeable differences (Bed: 99.8 ± 77.6 s, Walking: 92.9 ± 43.5 s, Wheelchair: 75.2 ± 79.5 s). As with the active preparation time (cf. Sect. 4.2), a high range between minimum and maximum value was observed: 1.0–289 s.

4.4 Pre-movement Time

Figure 6 presents the measured pre-movement times grouped by type of hospital ward and type of evacuation mode. Individual data points are colored according to the related drill, and each group's average pre-movement time is annotated.

The average pre-movement time over the entire study is 175 ± 107 s. The shortest average pre-movement time (115 s) was observed in the General Ward Space (GW), where the lowest maintenance intensity is to be expected. Conversely, the highest average pre-movement time (362 s) was measured in the High-Dependency Unit (HDU), where both

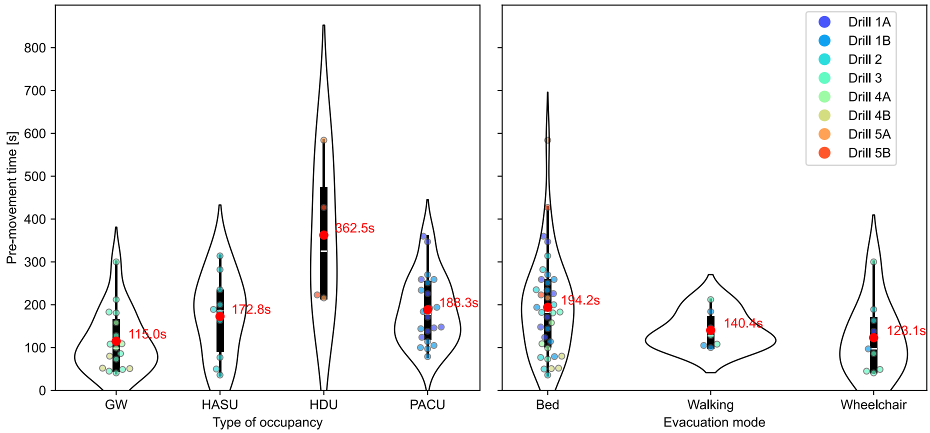


Fig. 6 Pre-movement time by type of occupancy [General Ward (GW), Hyper Acute Stroke Unit (HASU), High Dependency Unit (HDU), Post-Anesthesia Care Unit (PACU)], evacuation mode, and exercise. While the color of the scatter indicates the associated trial, the average pre-movement time of the entire group is annotated (Color figure online)

the intensive medical care requirements and the personnel capacity are highest, although less data was available for this unit.

The pre-movement times of the care units with medium care intensity (HASU and PACU) rank in between. It is noteworthy that the standard deviation for the HDU is twice as high (177 s) as that of the other wards. The pre-movement time ranges from 36 to 584 s. Despite this wide range, this observation is consistent with other studies (cf. Fig. 10).

Most of the data pertains to evacuation by bed, which leads to an average pre-movement time of 194 ± 115 s, while evacuation by walking requires a pre-movement time of 140 s, and by wheelchair requires a pre-movement time of 128 s. Notably, the pre-movement time associated with a bed is characterized by a high standard deviation (115 s), whereas the standard deviations for the other two modes are moderate (Walking: 43 s, Wheelchair: 85 s).

This pronounced distribution of pre-movement times indicates that the categorization of "bed" is useful in theoretical analysis, but the individual characteristics of this mode vary greatly. In the studies presented here, beds of two different types were used, which-depending on the level of care and ward-were also connected to different medical technical equipment. This variability in equipment requires different amounts of preparation time (cf. Sect. 4.2) and attention, and directly influences the proportion of the respective sub-phases in the pre-movement time (cf. Fig. 1). In contrast, in all cases, patients who were evacuated by walking or wheelchair modes were not connected to any medical devices and could simply be directly evacuated without delay.

In Drills 1A, 1B, 2, 3, 4A, and 4B the beds used for patients were primarily Hill-Rom® 900 SSR beds which have split siderails and external dimensions measuring 1.0 m wide by 2.15 m long. In Drills 5A and 5B (HDU) the beds used for patients were Linet® Multicare ICU beds which are an advanced ICU bed that can facilitate motorized patient transport and have external dimensions measuring 1.05 m wide by 2.37 m long.

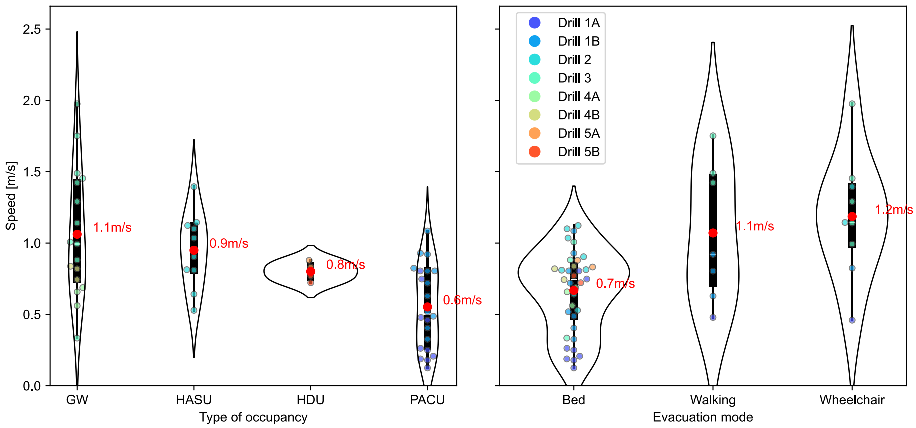


Fig. 7 Horizontal speed categorized by type of occupancy [General Ward (GW), Hyper Acute Stroke Unit (HASU), High Dependency Unit (HDU), Post-Anesthesia Care Unit (PACU)], evacuation mode, and exercise

4.5 Horizontal Speeds

Figure 7 presents the measured individual horizontal speed grouped by type of hospital ward and evacuation mode. Individual data points are colored according to the related drill, and each group's average speed is annotated.

The averaged individual speed over the entire study is $0.81 \pm 0.4\, m\, s^{-1}$. The slowest individual speed ($0.13\, m\, s^{-1}$) was observed in the PACU, while the fastest individual speed ($1.98\, m\, s^{-1}$) was measured in the GW. The speeds of patients in the care units HASU and HDU rank in between.

Overall, speed ranges from 0.13 to $1.98\, m\, s^{-1}$, an observation consistent with other studies (cf. Fig. 11).

As with the previous parameters, most of the data pertains to evacuation by bed, which results in an average speed of $0.67 \pm 0.28\, m\, s^{-1}$. Evacuation by walking results in an average speed of $1.07 \pm 0.48\, m\, s^{-1}$, while evacuation by wheelchair results in an average speed of $1.19 \pm 0.43\, m\, s^{-1}$.

Notably, the speeds associated with a bed exhibit a high range between minimum and maximum values ($0.13 - 1.12\, m\, s^{-1}$), while the ranges for the other two modes are smaller (Walking: $0.48 - 1.75\, m\, s^{-1}$, Wheelchair: $0.43 - 1.98\, m\, s^{-1}$).

Comparison of the mean speeds between the four occupation types shows only small differences (GW: $1.06 \pm 0.45\, m\, s^{-1}$, HASU: $0.95 \pm 0.26\, m\, s^{-1}$, HDU: $0.80 \pm 0.07\, m\, s^{-1}$, and PACU:$0.55 \pm 0.29\, m\, s^{-1}$).

4.6 Distribution Estimation

The data proposed in this work were used to calibrate continuous distributions for times and speeds. The proposed distributions were estimated using the *scipy.stats* Python library, which calibrates the proposed distributions using the Maximum Likelihood Estimation. In this paper, we consider four possible distributions, which are defined by two parameters: Lognormal distribution (Eq. 1), Gamma distribution (Eq. 2), Weibull distribution (Eq. 3), and Loglogistic distribution (Eq. 4).

$$\text{Lognormal: } F(x|a,b) = \frac{1}{b\sqrt{2\pi}} \int_0^x \exp\left(\frac{-(\ln(t) - a)^2}{2b^2}\right) \frac{1}{t}\, dt \tag{1}$$

$$\text{Gamma: } F(x|a,b) = \frac{1}{b^a \Gamma(a)} \int_0^x t^{a-1} e^{-\frac{t}{b}}\, dt \tag{2}$$

$$\text{Weibull: } F(x|a,b) = \int_0^x b a^{-b} t^{b-1} \exp\left(-(t/a)^b\right) dt \tag{3}$$

$$\text{Loglogistic: } F(x|a,b) = \frac{1}{1 + (x/a)^{-b}} \tag{4}$$

These distributions were chosen because they are only defined for positive values (i.e., negative times and speeds are not possible). Additionally, they have a skewed shape, which is common for evacuation times. Finally, these distributions are used in many well-known

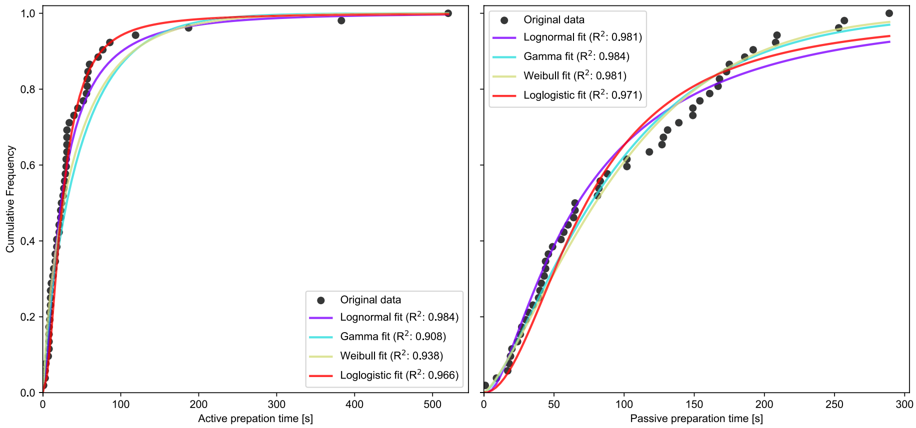


Fig. 8 Distribution fittings of active and passive preparation time

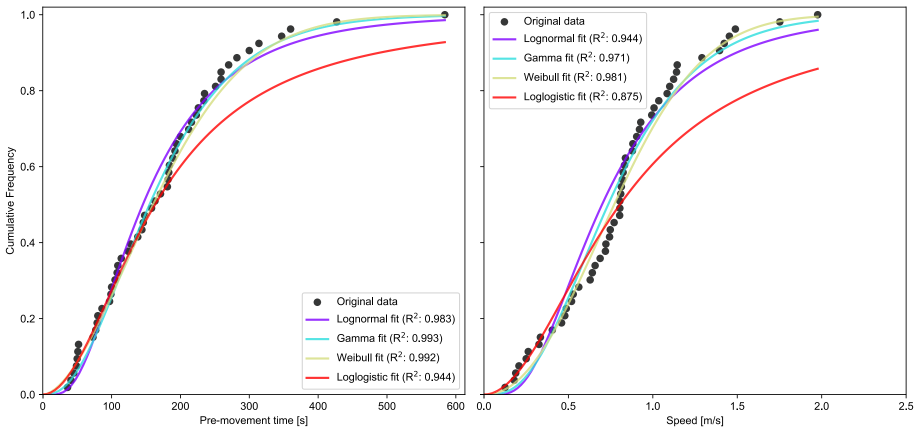


Fig. 9 Distribution fittings of pre-movement time and speed

Table 2 Distribution parameters for the active and passive preparation times (the distributions providing the best fitting are in *italic*)

Preparation time	Distribution	Parameter a	Parameter b	R^2
Active	*Lognormal*	1.144	23.390	0.984
	Gamma	0.816	59.191	0.908
	Weibull	0.819	41.869	0.938
	Loglogistic	2.000	25.000	0.966
Passive	Lognormal	1.017	66.951	0.981
	Gamma	1.496	64.818	0.984
	Weibull	1.313	105.022	0.981
	Loglogistic	2.000	73.000	0.971

Table 3 Distribution parameters for the pre-movement times and speeds (the distributions providing the best fitting are in *italic*)

Data	Distribution	Parameter a	Parameter b	R^2
Pre-movement	Lognormal	0.636	145.307	0.983
	Gamma	2.845	61.515	0.993
	Weibull	1.759	197.413	0.992
	Loglogistic	2.000	163.000	0.944
Speed	Lognormal	0.593	0.699	0.944
	Gamma	3.564	0.227	0.971
	Weibull	2.155	0.914	0.981
	Loglogistic	2.000	0.805	0.875

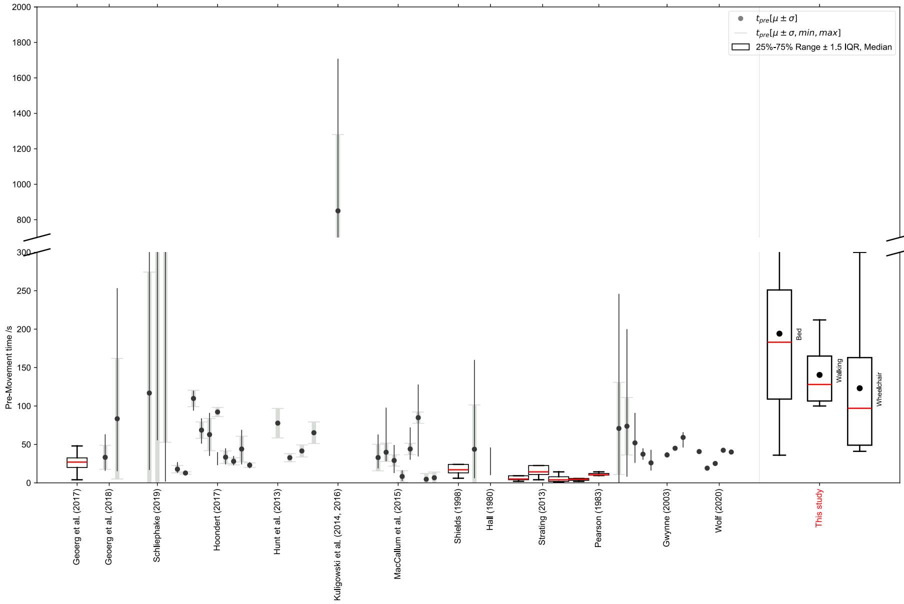


Fig. 10 Pre-movement times, denoted as t_{pre}, refer to the period before evacuation begins, particularly concerning individuals using assistive devices or those situated within a social facilities context, such as hospitals or residential homes. The term "pre-evacuation" is broadly defined here to encompass a wide range of specific subprocesses, including but not limited to decoupling. For data sources, refer to the following studies: [13, 15, 18–24, 28–31]. It should be noted that references exclusively available in German include [14, 32]

evacuation models [9]. The fitting of these four distributions is evaluated and compared using the R^2 fitting parameter. The results for all four distributions are presented within this section because some evacuation models may not be able to represent every distribution. This way, users can choose an alternative from the remaining distributions.

The estimated parameters for the distribution proposed in this work are illustrated in this section. Table 2 shows the estimated parameters for active and passive preparation time, while the estimated distributions are shown in Fig. 8. The findings indicate that Lognormal distribution provides the best fitting for the active preparation

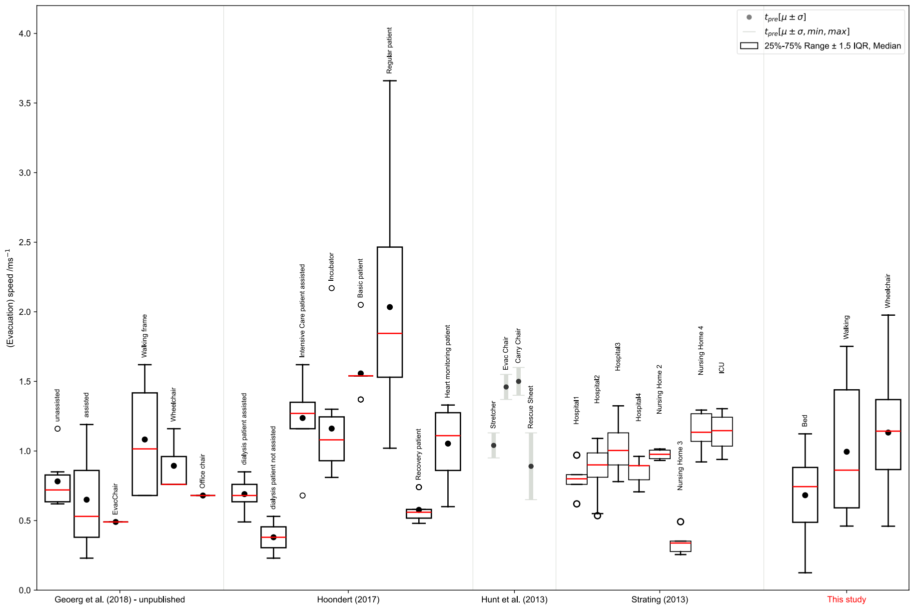


Fig. 11 Movement speeds v, are obtained from evacuation training exercises specifically conducted in settings such as hospitals and residential care facilities. The term "macroscopic" describes these speed values, indicating that they are calculated as average ratios of the time required to the distance covered. This approach provides a broad, aggregate view of movement speeds during evacuations. For data sources, refer to the following studies: [18, 20, 29]. It is important to note, however, that the data on the research conducted by Geoerg in 2018 has not been published yet and is therefore not accessible. More detailed information can be found in Appendix A

time ($R^2 = 0.984$), while Gamma distribution for the passive preparation times ($R^2 = 0.984$). Table 3 shows the estimated parameters for pre-evacuation times and speeds, while the estimated distributions are shown in Fig. 9. The findings indicate that Gamma distribution provides the best fitting for the pre-evacuation time ($R^2 = 0.993$), while Weibull distribution for the speeds ($R^2 = 0.981$).

5 Discussions

This work provides new insights to aid fire engineers in performing reliable evacuation simulations for hospitals. This was done by collecting new evacuation data from eight evacuation exercises carried out in two hospitals in New Zealand. The data was collected by video recording these evacuation exercises and manually extracting data on preparation times, pre-movement times, and evacuation speed. Further, the proposed data are compared and combined in this section (see Figs. 10, 11 and Table 5) to generate a new database for hospital evacuation. As such, this work is an extension of the pioneering work of Fahy and Proulx [5], who provided one of the first instances of a cohesive database of pre-movement times and walking speeds for use in evacuation modelling. The proposed finding in Sect. 4.2 shows substantial differences in the active preparation times depending on the type of area and evacuation mode (see Fig. 3). On the other hand, results in Sect. 4.3 show that the passive preparation times were equivalent when comparing the data for evacuation mode. However, there were substantial differences when aggregating the data by type of area (see Fig. 5). These findings suggest that it is necessary to consider personalized evacuation strategies that account for the different evacuation needs when running hospital evacuations. In fact, both evacuees with impairment and bedridden evacuees require more tailored solutions, which include better training for staff and the use of effective assistive devices. When comparing the passive and active times in Fig. 2, it is possible to observe that, except for HDU evacuations, the passive preparation times are substantially greater than the active preparation times. Noting that this passive phase is when there is no direct action toward effective evacuation, this indicates that the pre-evacuation time can be dramatically reduced, by increasing both the ratio of patients/staff and reducing the waiting time for equipment. Another interesting finding from the proposed evacuation investigation is the non-sequential behaviour of staff preparation activities. In fact, in several instances, staff did not complete the preparation activities for a single patient in a single time period. In fact, when staff were responsible for multiple patients, they did not prepare each one fully in sequence, but they were passing from one patient to another. When comparing the proposed pre-movement times with the one proposed in the literature, the results in Fig. 10 show that this new data has substantially higher average values than many other existing studies. This could be due to the evacuation drills in this study being conducted in working hospital wards with many patients, when compared with some of the existing data sources which were in outpatients facilities [13], office or residential buildings [15, 22–24], or used simplified and well-defined scenarios for research purposes with high staff:patient ratios [18, 19, 21, 25]. On the other hand, one of the limitations of this work is that it does not provide insight into the time required for specific activities during the active preparation times. This is due to the type of evacuation exercises which were not designed for this purpose. When focusing on the horizontal evacuation speed in Sect. 4.5, the results show that bed evacuation speeds are lower than walking and wheelchair evacuation speeds (see Fig. 7). On the other hand, the data in Fig. 2 highlights that the travel time is a relatively small component of the total evacuation with only a few outliers. This is because congestion was not observed in the evacuation exercises. As such, this work indicates the need to put more focus on the pre-evacuation stage when planning evacuations and/or running simulations. Finally, the proposed horizontal speed clearly overlaps with the data reported in the literature, as shown in Fig. 11.

With any experiment, there is a balance to be made between external and internal validity [26, 27]. Announced evacuation drills were the method used in these drills, primarily due to ethical limitations around conducting unannounced evacuation drills on real patients within each of these hospital spaces. While there is a reduction in urgency and surprise associated with an announced evacuation, there are still meaningful insights to be gained with such an activity. Further, only a single sensory input (aural alerting devices) was provided to participants. The use of other sensory inputs, such as visual, olfactory, or somatosensory inputs, is likely to improve a sense of realism and motivation and would be useful to explore in future work. Patients were healthy volunteers and not actual patients within the hospital, this was due to ethical considerations and to work within the operational requirements of a working hospital. The use of healthy volunteers aids in the reduction in realism for staff, having patients who are not only dressed differently and lying on top of a bed but who are not physically connected to the medical devices within the hospital. One avenue for future exploration could be to use actors who are dressed like patients, lying in bed, and actually connected (where feasible) to monitoring and medical equipment. This scenario could be further enhanced by limiting the number of observers who both clutter the area of observation and also add to the artifice of the scenario, as well as adding a narrative portion to describe the situation as not just a drill but as an actual emergency evacuation. Finally, there were observable differences between types of spaces within the hospital evacuation drills carried out in this study, particularly between higher-acuity spaces and low-acuity spaces (e.g. GW spaces). There is a need to gain a better understanding of some of the differences between high-acuity spaces (e.g. HDU) and low-acuity spaces (e.g. GW spaces). It seems reasonable to deduce this difference is due to additional medical equipment, which takes more time to disconnect. However, a detailed simulation study would be beneficial in collecting this type of data on the relationship between medical acuity and preparation times.

6 Conclusions

The findings from this research highlight some of the nuanced behaviours which occur during the pre-movement phases of the assisted evacuation of inpatients from a hospital facility. An understanding of the presence and magnitude of these components is crucial to enable appropriate inputs for modelling hospital spaces where patients are unable to egress without assistance.

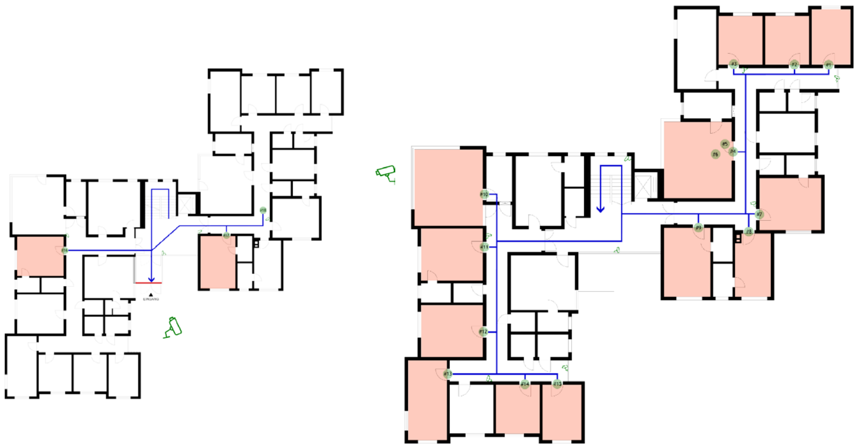
Results suggest that depending on the type of space, there can be considerable differences in the proportion of time spent actively preparing a patient for egress versus time spent waiting for equipment or staff to become available. This finding is important as it highlights the influence of staff:patient ratios and the availability of required portable medical equipment, on the assisted evacuation of inpatients.

For the highest acuity spaces studied (HDU), it was observed that the high staff:patient ratios meant that the passive preparation times were very minimal with a high proportion of the time spent actively preparing the patient for egress. Even with this considerable resource available these patients represented the longest pre-movement times by a large margin. The reason for this is the additional equipment used for these patients which required long preparation times to disconnect and make ready for evacuation.

Overall, this research highlights the value to be gained by a deeper understanding of the sub-components that comprise the pre-movement phases of evacuation in a hospital occupancy. While conducted in hospitals, the results have value for other occupancy types where evacuees require assistance to evacuate. While this work contributes useful data for egress modelling, it also paves the way for further work to develop an understanding of the factors which influence the active preparation phases such as the level of acuity and medical equipment.

Appendix A: Introducing Geoerg (2018)–Data

An announced evacuation drill was carried out to compare the movement behavior of people with and without disabilities. The study took place in a residential community for people with disabilities in Germany.



(a) Ground floor (b) Upper floor

Fig. 12 Floor plans presenting the general setup including starting positions of residents, camera positions, and movement directions. Blue lines represent the direction of movement towards the exit of the building (red line). Light green circles represent the starting positions of the residents (Color figure online)

Setting and Participants

The study was conducted in a residential community used to accommodate individuals with physical, mental, or age-related disabilities. The building included ground and upper floors with designated emergency exits and evacuation routes. The participants included residents (n = 28) of the community and their caregivers (n = 6) (Fig. 12).

Methods

An unannounced evacuation drill was carried out to simulate an emergency scenario. The drill was initiated manually by a member of the organization team at 19:15 h on 04 December 2017. Fourteen fixed wide-angle cameras (GoPro Hero5 and Hero6) were placed throughout the building to capture the evacuation process. Cameras were positioned in hallways, staircases, and external areas to ensure comprehensive coverage without intruding into private rooms. With the CCTV data, it was possible to calculate reaction times, horizontal and vertical movement times, and the overall evacuation duration of the participants. The University of Wuppertal's (Germany) ethics committee has approved the study's realization without any ethical concerns.

Measurements

The collected data were analyzed to determine the reaction times, horizontal and vertical movement speeds, and the overall evacuation duration. Comparisons were made between individuals with and without disabilities to identify significant differences in evacuation behavior and efficiency. Four dependent variables were measured from the captured CCTV:

Table 4 Main results of Geoerg 2018. Floors are named Upper (UPR) and Ground Floor (GF)

Participant ID	Starting floor	Sex	Type of assistance	Preperation time [s]	Total evacuation time [s]	Vertical movement time [s]	Horizontal movement time [s]	Vertical speed $[m\,s^{-1}]$	Horizontal speed $[m\,s^{-1}]$
6	UPR	F	Assistance	55	589	40	494	0.23	0.04
17	GF	F	Walking frame	341	110	0	97	–	0.13
9	UPR	M	Walking frame	342	501	72	87	0.13	0.14
5	UPR	F	Walking frame	50	247	74	124	0.12	0.15
3	UPR	F	Walking frame	62	306	79	166	0.12	0.15
14	UPR	F	None	27	249	39	182	0.23	0.16
1	UPR	M	None	63	245	18	165	0.52	0.18
8	UPR	M	Special request	607	702	21	73	0.43	0.22
11	UPR	F	Wheelchair	905	1028	41	82	0.22	0.22
18	GF	F	Wheelchair	2	70	0	69	–	0.23
12	UPR	F	Assistance	144	284	44	96	0.21	0.26
15	UPR	F	Assistance	774	929	34	121	0.27	0.27
4	UPR	F	None	26	129	35	68	0.27	0.27
13	UPR	M	Wheelchair	712	818	36	70	0.25	0.43
2	UPR	M	Wheelchair	626	720	34	60	0.27	0.45
7	UPR	F	None	56	118	32	30	0.28	0.52
10	UPR	M	None	235	316	48	34	0.19	0.54
16	GF	F	Wheelchair	55	68	0	12	–	0.96
23	GF	F	None	–	35	–	–	–	–
24	GF	M	None	–	50	–	–	–	–
25	GF	F	Wheelchair	–	92	–	–	–	–
26	GF	M	Assistance	–	93	–	–	–	–
27	GF	F	Walking frame	–	97	–	–	–	–
22	GF	F	Wheelchair	–	284	–	–	–	–

Table 4 (continued)

Participant ID	Starting floor	Sex	Type of assistance	Preperation time [s]	Total evacuation time [s]	Vertical movement time [s]	Horizontal movement time [s]	Vertical speed [$m\,s^{-1}$]	Horizontal speed [$m\,s^{-1}$]
21	GF	F	Assistance	–	301	–	–	–	–
20	GF	M	None	–	456	–	–	–	–

1. *Reaction times*, defined as the interval between the alarm sound starts and the moment participants cross the threshold of their rooms,
2. *Horizontal movement times*, defined as the time interval between passing the threshold line in front of the rooms until reaching the exit of the building,
3. *Vertical movement times*, which is the time difference between the top and the bottom of staircases,
4. *Use of assistive devices* is a qualitative analysis of assistive devices' use and handling procedures, such as escape chairs, etc.

Main Results

Various assistive devices were used, including manual wheelchairs and the escape chair. On horizontal routes, rollators and wheelchairs were primarily used, while for vertical movement, the escape chair was frequently employed. The use of assistive devices often resulted in lower speeds, especially for the escape chair, requiring significant assistance and practice for efficient use (Table 4).

Reaction times varied significantly among the residents, without a striking link between reaction time and physical disability. The measured reaction times ranged from 13 to 905 s, with an average of 264 s to react to the alarm. Individuals without disabilities had reaction times between 60 and 120 s, while elderly participants had times between 90 and 150 s. The average reaction time in the study was significantly longer at 264 s.

Horizontal movement time was measured from the (private) room exit line until reaching the building's main exit. For residents from the ground floor (GF), only horizontal movement time was recorded. For residents from the upper floor (UPR), both horizontal and vertical movement times were recorded. The longest horizontal movement time noted was 312 s longer than the second slowest, due to a resident wandering the corridor for an extended period before being assisted.

Vertical movement time was recorded from the midpoint of the marked area on the upper floor to one meter past the last step on the ground floor. The average vertical movement speed was 0.25 $m\,s^{-1}$, with a range between 0.12 and 0.52 $m\,s^{-1}$. This speed is lower than the horizontal movement speed due to the use of the Escape-Chair and the additional assistance required for stair navigation.

Appendix B: Tabled Data

See Tables 5 and 6.

Table 5 Tabled data summary by evacuation device

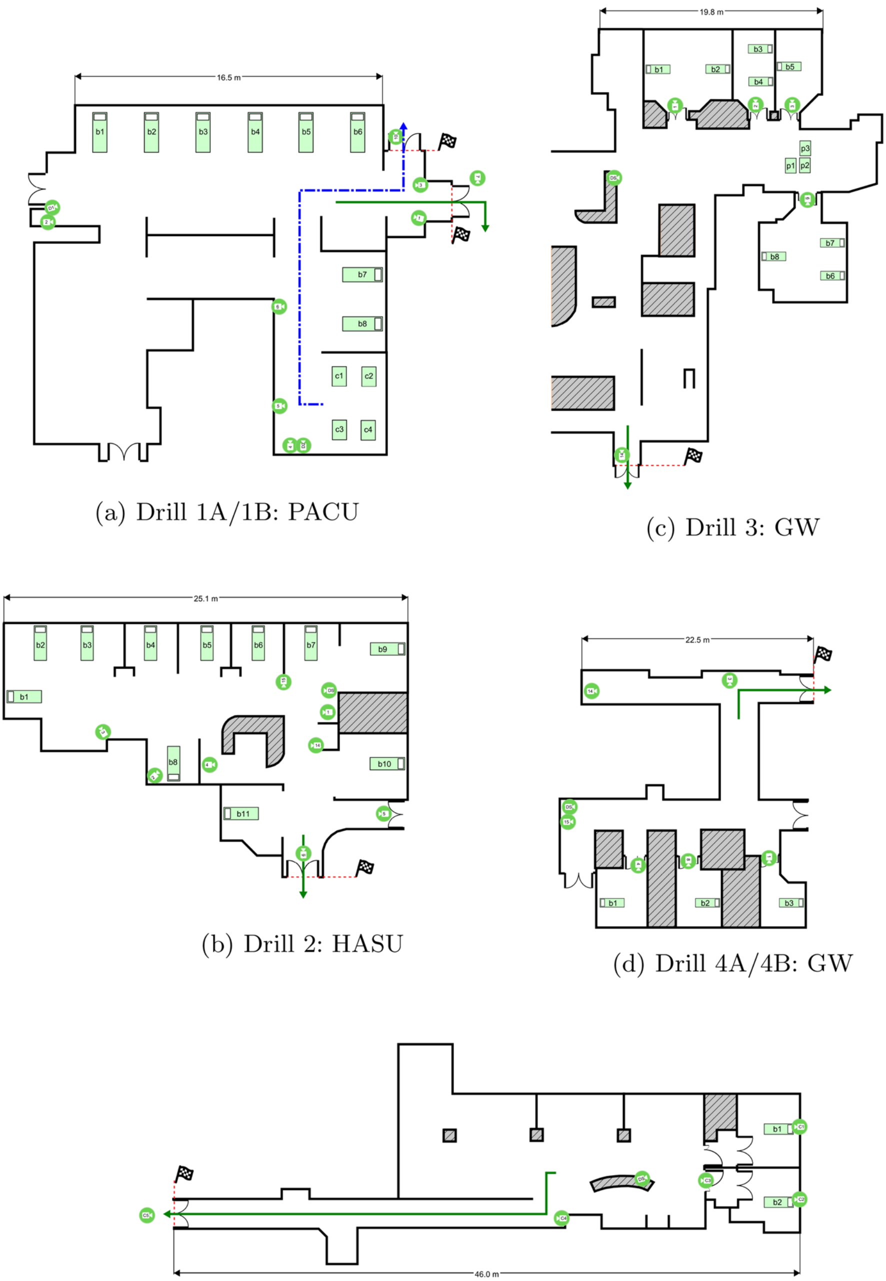
	n	Mean [SD, min − max]
Active preparation time [s]		
Bed	37	65.2 [106.7, 4.0–526.0]
Walking	8	16.5 [8.4, 8.0–31.0]
Wheelchair	10	25.5 [18.5, 1.0–52.0]
Passive preparation time [s]		
Bed	37	129.0 [83.4, 7.0–306.0]
Walking	8	124.6 [33.5, 92.0–191.0]
Wheelchair	10	111.2 [80.5, 40.0–269.0]
Pre-movement time [s]		
Bed	37	194.2 [115.2, 36.0–584.0]
Walking	8	141.1 [40.0, 100.0–212.0]
Wheelchair	10	136.7 [91.0, 41.0–300.0]
Speed [$m\,s^{-1}$]		
Bed	37	0.7 [0.3, 0.1–1.1]
Walking	8	1.0 [0.5, 0.5–1.8]
Wheelchair	10	1.1 [0.4, 0.5–2.0]

Table 6 Tabled data summary by type of occupancy (General Ward (GW), Hyper Acute Stroke Unit (HASU), High Dependency Unit (HDU), Post-Anesthesia Care Unit (PACU)

	n	Mean [SD, min − max]
Active preparation time [s]		
GW	17	19.2 [18.5, 1.0–77.0]
HSU	10	18.5 [11.9, 8.0–45.0]
HDU	4	329.0 [156.8, 187.0–526.0]
PACU	24	40.5 [26.8, 7.0–119.0]
Passive preparation time [s]		
GW	17	95.8 [66.9, 40.0–269.0]
HSU	10	154.3 [95.8, 26.0–306.0]
HDU	4	34.0 [22.0, 7.0–58.0]
PACU	24	148.9 [63.8, 55.0–276.0]
Pre-movement time [s]		
GW	17	115.0 [71.4, 41.0–300.0]
HSU	10	172.8 [94.2, 36.0–314.0]
HDU	4	363.0 [176.7, 214.0–584.0]
PACU	24	189.5 [77.6, 79.0–360.0]
Speed [$m\,s^{-1}$]		
GW	17	1.1 [0.4, 0.3–2.0]
HSU	10	0.9 [0.3, 0.5–1.4]
HDU	4	0.9 [0.2, 0.7–1.1]
PACU	24	0.6 [0.3, 0.1–1.1]

Appendix C Floor Plans

See Fig. 13.



(a) Drill 1A/1B: PACU

(c) Drill 3: GW

(b) Drill 2: HASU

(d) Drill 4A/4B: GW

(e) Drill 5A/5B: HDU Isolation

Fig. 13 Floor plans presenting the general setup and type of occupancy [General Ward (GW), Hyper Acute Stroke Unit (HASU), High Dependency Unit (HDU), Post-Anesthesia Care Unit (PACU)], including dimensions, camera positions, and movement directions for all drills. Green lines represent the exits used for beds, while the blue dashed lines in Fig. 13a indicate where wheelchair and walking patients used a different exit. The dotted red line and finish line flag represent each patient's 'finish line' (Color figure online)

Acknowledgements PG: Part of this work has been performed within the research program Safety for people with physical, mental or age-related disabilities (SiME) supported by the German Federal Ministry of Education and Research - BMBF (Grant No 13N13946). Dr Geoerg thanks the SFPE Foundation for financial support with the Dr. Guylène Proulx, OC Scholarship in 2017. He would also like to thank Lea Schliephake for extracting the times from the video footage for the Geoerg 2018 data. LdS: Icons used in images are reproduced from the Noun project in accordance with the Creative Commons 3.0 license; credits: Md. Kabir Hossain, Joseph Joestar, Danang Marhendra, and Roberto Chiaveri. RL: Dr Lovreglio thanks the NZ Ministry of Business, Innovation & Employment and Royal Society Te Aparangi for funding his research through the Marsden Fast Start (MAU2204) and the Rutherford Discovery Fellowship (RDFMAU2201). All authors extend their gratitude to all participants and collaborators for their involvement and support in the drills and evacuation studies.

Author Contributions Paul Geoerg: Conceptualization, Methodology, Software, Formal analysis, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization. Luke de Schot: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization. Ruggiero Lovreglio: Conceptualization, Methodology, Investigation, Resources, Writing—Original Draft, Writing—Review & Editing, Supervision, Project administration, Funding acquisition. All authors have read and agreed to the published version of the manuscript. All authors reviewed the manuscript.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. Open-access funding is provided by Massey University of New Zealand.

Data Availability A de-identified dataset generated and analyzed during the current study is available from the corresponding author upon reasonable request.

Declarations

Ethical Approval The project was subject to review and approval by the Massey University Ethics Board. 'Patients' were volunteer observers comprising other staff members and other interested stakeholders such as consultants, fire brigade staff, and local council staff. The research was classified as low risk. Key considerations included informed and voluntary consent of participants, and privacy and confidentiality of participants and their data.

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