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Technical Note

Evacuating Vulnerable People During a Tsunami Disaster in Japan: A Simulation Using Wheelchairs

Nobuhito OHTSU [1*] and Akihiko HOKUGO [2]

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Abstract Safe, rapid evacuation during natural disasters is particularly challenging for people who are vulnerable and/or need assistance. This study evaluated the feasibility of an evacuation route from a residential area to a designated destination for wheelchair-bound people and their caregivers. Thirteen individuals participated in an evacuation simulation in which they pushed wheelchairs carrying individuals from a start point to a designated destination along a specified route. The simulation was implemented on September 9, 2018, between 9:00 AM and noon. The weather was recorded hourly. Individuals in the wheelchairs were weighted to equal the average weight for Japanese men aged ≥65 years. The route comprised three sections: two were within the predicted tsunami inundation zone and one was on higher ground. The gradients, distances, and altitudes of the three sections were determined using official documentation. Participants were videotaped as they traversed the route, and their speeds and times recorded as the wheelchairs crossed from one section to the next. Immediately upon reaching the destination, participants completed a questionnaire assessing the physical effects of the activity. The route was 280.6 m long with a total vertical increase of 13.9 m. Mean total transit time was 3 min 25 s, and the mean time taken to evacuate the predicted tsunami inundation zone (at 210.2 m) was 2 min 15 s. All participants' speeds were slowest in the third section, which had the steepest gradient (11.14%). Ten participants reported moderate difficulty, difficulty pushing, and sweating. Nine participants reported shortness of breath. The results support use of the evacuation destination during a predicted earthquake tsunami ≥8 m high at landfall.

Keywords: tsunami evacuation, vulnerable people, wheelchair

[1] Ministry of Internal Affairs and Communications, Japan, National Research Institute of Fire and Disaster
* Corresponding author email: n.ohtsu@soumu.go.jp
[2] Research Center for Urban Safety and Security, Kobe University

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1. INTRODUCTION

It is important that residents who need assistance and their caregivers are immediately evacuated when a tsunami is imminent. To effectively accomplish this, disaster prevention organizations need to know the best ways to evacuate vulnerable people and how rapidly this could be achieved. A previous study on vulnerabilities in cyclone evacuation discussed the role of poverty and resultant lack of knowledge and awareness in evacuation (Haque E., and Blair D. 1992). However, excepting our own work, there is no research focusing on the physical vulnerability of people with disabilities and older people in evacuations. Previous studies have measured the transportation speed of vulnerable people under controlled conditions on an experimental course (Ohtsu et al. 2020) and using four types of transportation equipment in drills in urban areas (Ohtsu and Hokugo 2019). Some studies have measured transit speeds along evacuation routes within a tsunami evacuation tower (Tanaka et al. 2019), and the amount of time taken to walk an evacuation route during an evacuation drill (Nihei and Hashimoto 2013, and Muraishi 2014). However, the effect of gradient on evacuation time has not been studied. Evacuation drills have been conducted in Kainan City, Japan, in which community disaster prevention organizations and/or units have assembled and subsequently walked to evacuation destinations. However, such drills have not always considered individual circumstances, including mobility and speed. To support fire departments in assisting residents, it is important to be able to predict residents' mobility by determining how fast wheelchairs can transport people.

One way to prepare for a tsunami or similar natural disaster is to practice before the event moving groups of people to designated safe shelters at higher altitude locations. However, this approach has not been implemented in all the relevant coastal municipalities, and evacuation during an event with no previous practice is risky. Plans and drills are essential disaster prevention activities that facilitate effective evacuations and maximize protection from harm during a disaster. To develop plans and drills, it is important to determine how much time it takes to evacuate all residents in a particular area.

To address this knowledge gap, this study conducted a hands-on simulation experiment of the evacuation speed of people in wheelchairs. The simulation was conducted in Kainan City, Wakayama Prefecture, Japan, which is within the estimated tsunami inundation zone in the event of a great Nankai Trough earthquake. Over the last few decades, research has been conducted on predicted tsunamis caused by undersea earthquakes near the coast of Japan. This research has enabled the estimation of tsunami heights in coastal areas and tsunami arrival times from the earthquake epicenter. Estimated tsunami arrival times are recorded and publicly available via hazard maps published by local governments. People are required to evacuate to an altitude higher than the estimated tsunami height within the tsunami arrival time. The aim of the present study was to examine the evacuation time of the target population to determine if this requirement is achievable, and whether the target population is at risk. The estimated tsunami inundation area as specified by the Kainan City hazard map is shown in Fig. 1. The Ministry of Land, Infrastructure, Transport and Tourism has predicted that a great Nankai

Trough earthquake would have a magnitude of 9.1, a maximum tsunami height of 8 m, and that the time between the earthquake and a 1 m tsunami landfall would be 43 min in Shimotsu, Kainan City. The maximum expected inundation depth of the study area inundation zone shown in Fig. 1 ranges from 2 to 5 m and 5 to 10 m (as shown in Fig. 2), with most of the evacuation route subject to substantial inundation (*i.e.*, inundation of up to three building stories). A tsunami occurs following earthquake tremors in the ocean trench. Generally, to the place closer to the trench tsunami reaches earlier, whereas to the place further away from the trench tsunami takes longer time to reach. This study was conducted in a small part of the area of expected tsunami damage. The aim of the simulation was to clarify the evacuation speed and amount of time needed to evacuate wheelchair-bound people from the inundation zone to a public park designated as the evacuation destination for vulnerable people (in wheelchairs) and their supporters. This study is unique because it evaluated the route designated for community disaster prevention organizations during a disaster; therefore, the findings contribute toward a better understanding of the effectiveness of the current tsunami evacuation plans. The simulation used wheelchairs for transit because the effect of traffic congestion on automobile transit is unpredictable; therefore, cars are not reliable evacuation modes to study in simulations. Some vulnerable people may be moved on stretchers without back supports or wheels; however, this method requires supporters to bear the weight of the vulnerable people. Stretchers are not a feasible option in aging rural areas because supporters are likely to be older adults assisting other older adults over relatively long distances. In these contexts, wheelchairs are the most practical way to evacuate vulnerable people.

2. MATERIALS AND METHODS

The simulation was conducted in the Shimotsu area of Kainan City, Wakayama Prefecture, Japan, on September 9, 2018. Fig. 1 shows the evacuation route and Table 1 describes the topography of the route's three sections. The route began within the predicted tsunami inundation zone of a great Nankai Trough earthquake. The route ended at the entrance to Minato Fureai Park, which is outside and higher than the inundation zone. The Kainan City Tsunami Evacuation Plan designated this park, which is on high ground, as an emergency evacuation destination (Kainan City 2017). The route covered 280.6 m and was divided into three sections for the simulation. Section 1 had a mild gradient (0.09%), and Sections 2 and 3 had relatively steep gradients. Sections 1 and 2 were within and Section 3 was outside the predicted tsunami inundation zone. The difference in altitude between the route's start and endpoints was 13.9 m. This route was selected as an evacuation route for the simulation because it is wide and has a low density of old wooden buildings, and old brick walls; thus, the possibility of route blockage is low.

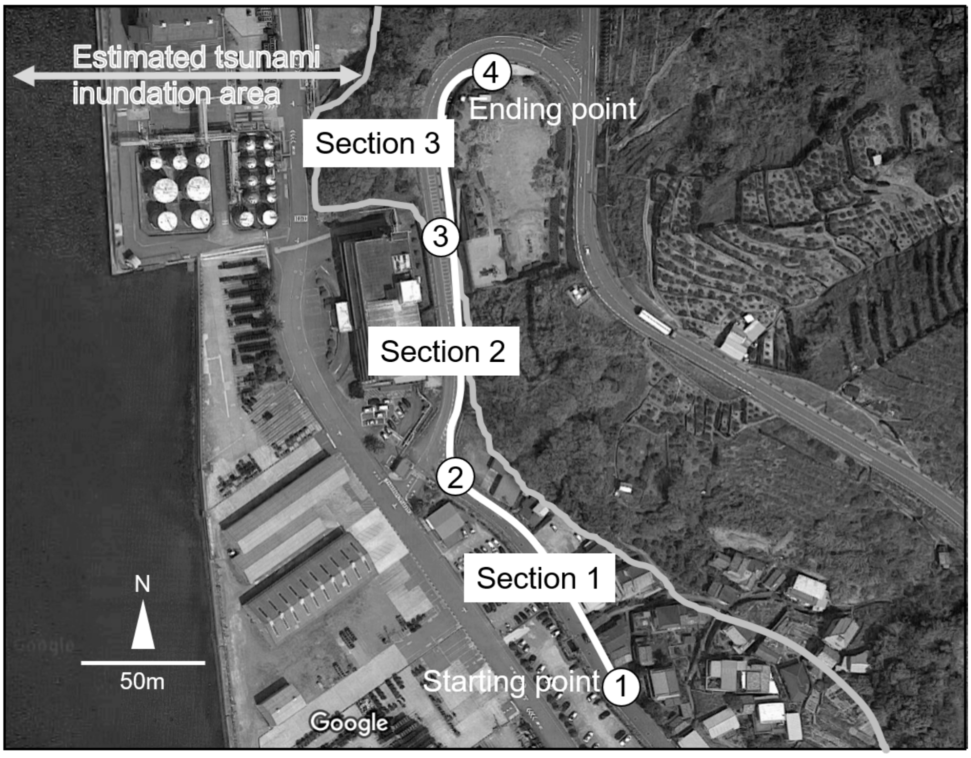

Figure 1. Evacuation Route. Numbers in circles represent the points at which the time was recorded. Source: Google Earth (accessed on October 20, 2018)

Fig. 2 shows the hazard map of the study area and the maximum inundation depth of the inundation area in Kainan City.

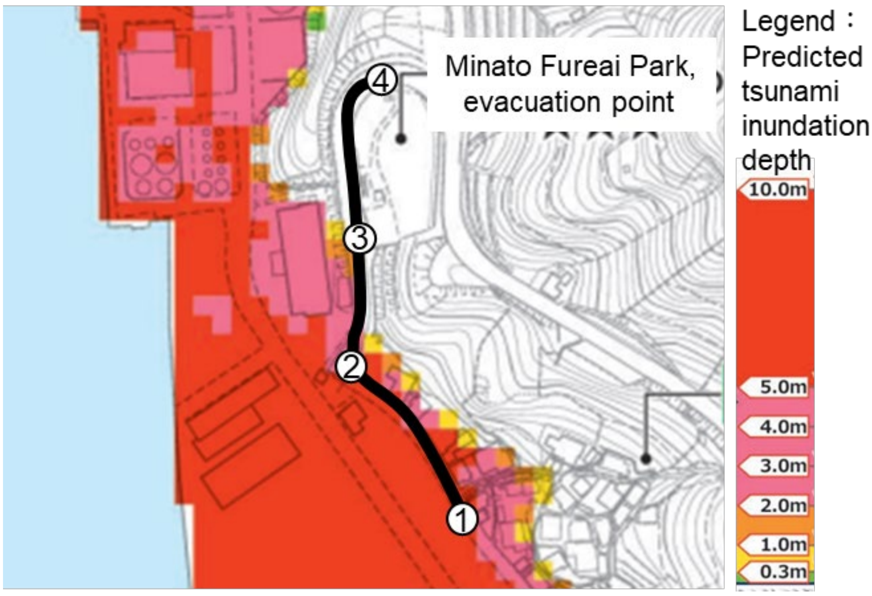

Figure 2. Hazard Map of Shimotsu Area, Kainan City. Magnified image of the area of interest shown in Fig. 1. Source: Kainan City (accessed on December 4, 2021)

Table 1. Topographical Information and Evacuation Route Length by Section.

	Section			Total
	1	2	3	
Average gradient (percentage)	0.09	6.00	11.14	4.96
Length (meters)	110.0	100.0	70.0	
Altitude (meters)	0.1	6.0	7.8	13.9
Transit distance (meters)	110.0	100.2	70.4	280.6

The evacuation destination used in this simulation is listed in the Kainan City Regional Disaster Prevention Plan (Kainan City 2017). The city government has designated 98 evacuation sites, of which No. 62 is Minato Fureai Park. The route designed for this study is a "horizontal evacuation" route to higher ground, rather than a "vertical evacuation" route to a higher floor of a building. Although this area contains a high-rise building, it is in a factory that is surrounded by wire mesh and so is not an easily accessible evacuation point. Therefore, evacuation to higher ground is the only option in this area. The evacuation route extends from the residential area to the destination and has a maximum gradient of 11.14%, which allows for transit by wheelchair. The streets along the route are wide enough to allow people moving at a normal speed to pass slower moving individuals and wheelchairs. The altitude of the destination is 16 m, which is twice the predicted maximum height of a tsunami in Kainan City in the event of a great Nankai Trough earthquake (Kainan City 2017). Roads leading to higher ground from the destination have been constructed; these could be used as routes for secondary evacuations to higher ground if the tsunami wave height is greater than expected or if evacuees need to be moved to shelters. Minato Fureai Park is large enough to be used as a central base for disaster prevention activities, and contains facilities for storing materials and equipment used by community disaster prevention organizations.

Modes of transit

Two types of wheelchairs were used for the simulation: Wheelchair A (W-A) and Wheelchair B (W-B). W-A is slightly lighter than W-B (17.0 kg and 17.9 kg, respectively), and differs slightly in size to W-B (85 cm versus 88 cm high, 68 cm versus 62 cm wide, and 110 cm versus 104 cm deep, respectively).

Simulation procedure

Participants

There were 26 participants in this study. Participants were university students, staff, and teachers who were recruited by the authors. All participants took part voluntarily. Thirteen participants (men and women aged 23–56 years) were assigned to push the wheelchairs.

Thirteen different participants were pushed in the wheelchairs. The body weight of each wheelchair-bound individual was supplemented to equal 62.04 kg, which is the average weight for Japanese men aged ≥65 years (Bureau of Statistics of the Ministry of Internal Affairs and Communications 2011).

Procedure

First, the 13 participants assigned to push the wheelchairs were given the following instructions: “Today, we are conducting a simulation about moving vulnerable people. You need to pretend that you are evacuating from a tsunami inundation zone with a vulnerable person in a wheelchair. You must push the wheelchair with the person sitting in it from the designated starting point to the designated endpoint at the park. You must put the safety of the vulnerable person first while pushing the wheelchair along the evacuation route as quickly as possible.” Researchers accompanied each participant as she or he pushed the wheelchair along the route and videotaped the process from beginning to end. The video content was used to determine participants’ evacuation time, which was used to calculate evacuation speed. The time at which the rear wheel of the wheelchair passed over each of the four designated points (see Fig. 1) was recorded. Point 1 was the starting point and Point 4 was the end of the route. Points 1 and 2 were inside the inundation zone, Point 4 was outside the zone, and Point 3 was the transitional point. Fig. 2 shows a researcher filming a participant pushing a wheelchair during the simulation. The study comprised the simulation (*i.e.*, the activity of pushing the wheelchair) followed by a questionnaire (Fig. 4).

Figure 3. Photograph of the Simulation in Progress (Section 2 on the Route). Source: *Author*, September 9, 2018

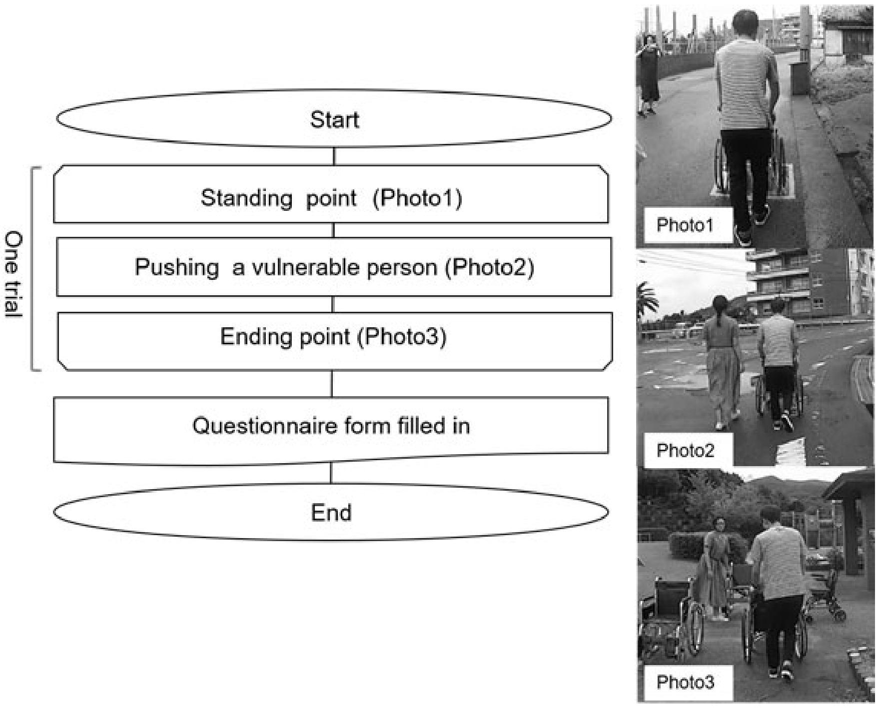

Figure 4. Study Procedure. 1 Source: *Author*, September 9, 2018

3. RESULTS

Weather conditions

The weather conditions between 9:00 AM and noon on September 9, 2018, are shown in Table 3. It was cloudy (with 15.0 km visibility), the temperature range was 26.1−28.0℃, and there was no precipitation (Japan Meteorological Agency 2019). Participants started the simulation sequentially rather than at the same time; therefore, each participant had a different start time.

Table 3. Weather Conditions on the Route During the Simulation.

Time	Air pressure (hPa)		Dew point (C)	Steam pressure (hPa)	Humidity (percent)	Wind velocity	Wind direction
	Land	Sea					
9:00	1011.0	1013.1	23.9	29.6	85	4.3	S
10:00	1011.2	1013.3	23.8	29.4	87	2.1	E-NE
11:00	1011.1	1013.2	22.6	27.4	73	4.7	S
Noon	1010.7	1012.8	22.9	28.0	74	5.6	S-SW
September average*	1010.7	1012.8	24.9	21.8	69	3.5	E-NE

*Average value of the weather in September in Wakayama City for 30 years from 1991 to 2020 (Japan Meteorological Agency, 2021).

Transit speed and time

All 13 wheelchair-pushing participants completed the route without pausing and there was no interference from moving bicycles or pedestrians. For all participants, transit speed was the slowest in Section 3, which had the steepest gradient on the route. The slowest speed in Section 1 (1.43 m/s) was shown by a 26-year-old male participant. A 56-year-old female participant had the slowest speed in Section 2 (1.28 m/s). The slowest speed in Section 3 was 0.88 m/s, which was shared by a male participant aged 26 years and a female participant aged 29 years. The longest transit time from beginning to end (Point 1 to Point 4) was 3 min 54 s, and the shortest transit time was 3 min 10 s. The maximum time it took to reach and pass Point 3 (which was the point at which the route left the predicted tsunami inundation zone) was 2 min 35 s, and the slowest time to that point was 1 min 56 s. Table 4 shows the transit speeds and times of each participant.

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Table 4. Transit Speeds and Times of the 13 Participants.

Subject	Age	Gender	Transit speed (m/s)				Transit time (hh:mm:ss)
			Section				
			1	2	3	Total	
1	20s	Male	1.43	1.62	1.14	1.40	0:03:21
2	30s	Male	1.96	1.52	1.01	1.46	0:03:12
3	50s	Female	1.45	1.28	0.88	1.20	0:03:54
4	20s	Female	1.80	1.67	0.93	1.43	0:03:16
5	20s	Male	1.53	1.67	1.19	1.47	0:03:11
6	20s	Male	1.45	1.47	1.01	1.31	0:03:34
7	20s	Female	1.53	1.52	0.90	1.30	0:03:36
8	20s	Male	1.72	1.54	1.10	1.45	0:03:13
9	50s	Female	1.57	1.39	0.94	1.29	0:03:37
10	50s	Male	1.57	1.54	1.08	1.40	0:03:20
11	20s	Female	1.62	1.52	0.88	1.31	0:03:34
12	50s	Female	1.55	1.67	1.19	1.48	0:03:10
13	40s	Female	1.64	1.57	0.99	1.39	0:03:22
Max	-	-	1.96	1.67	1.19	1.48	0:03:54
Min	-	-	1.43	1.28	0.88	1.20	0:03:10
Average	-	-	1.60	1.54	1.02	1.38	0:03:25
Standard deviation	-	-	0.15	0.11	0.11	0.08	

Relationship of transit speed to gradient and altitude

Changes in speed throughout the route

Fig. 5 shows the relationship between transit speed and gradient by section. This relationship seemed to be associated with gradient. Speed was slower in Section 3, where the gradient was steepest. It is reasonable to assume that speed decreased over time owing to participants becoming tired and the increase in the gradient of each section along the route.

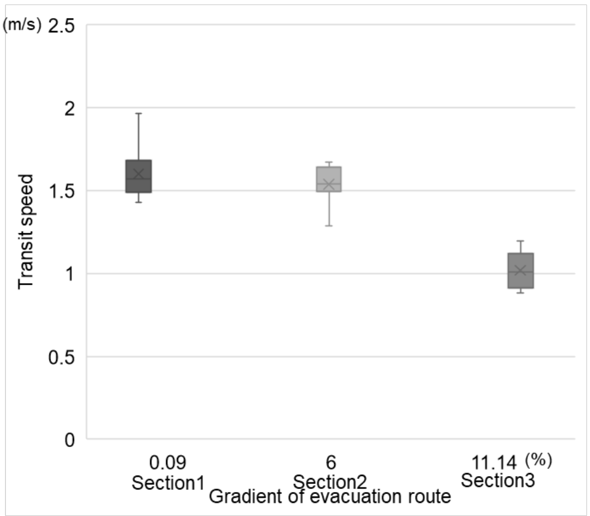

Figure 5. Relationship Between Transit Speed and Gradient.

Relationship between time and altitude

The amount of time it took to reach and pass Point 3, where the route left the predicted tsunami inundation zone, was the total transit time from the beginning of the route to the end of Section 2. The longest time it took to cross Point 3 was 2 min 35 s, and the shortest time it took to cross Point 3 was 1 min 56 s (average = 2 min 15 s). At Point 3, the altitude was 8 m, which is the predicted maximum tsunami height. Fig. 6 shows the relationship between time spent and altitude for each participant and the point at which each participant crossed Point 3.

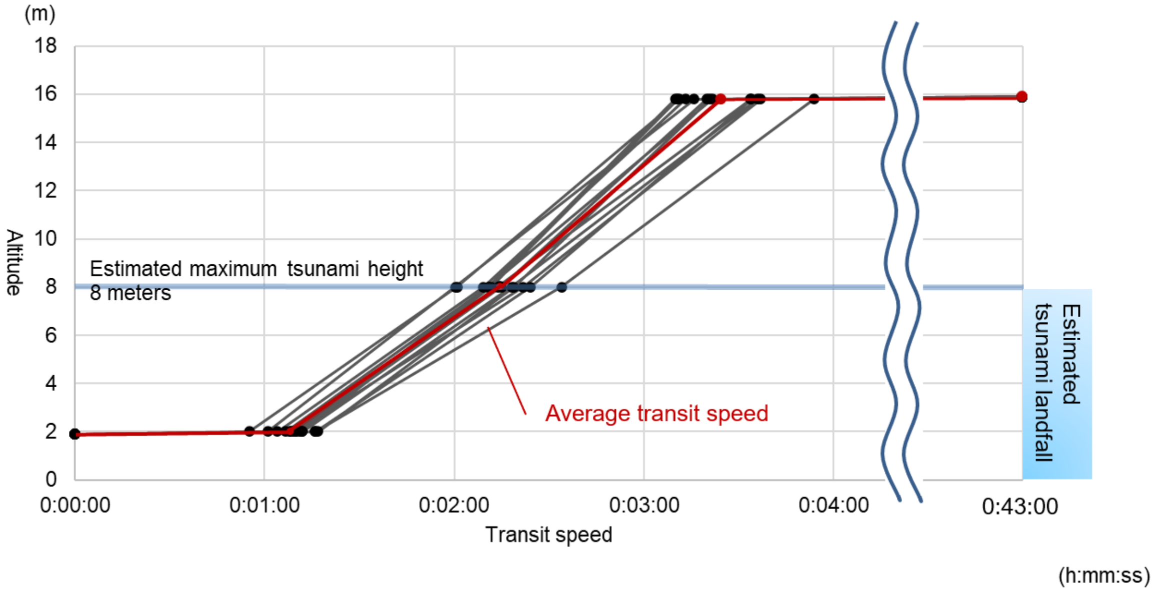

Figure 6. Relationship Between Time and Altitude Along the Route by Participant.

Questionnaire results

At the end of the route, participants completed a questionnaire to assess their previous experiences, how difficult they found the activity, the extent of physical difficulty, and their physical responses to the activity. The responses to the questions about previous experience with wheelchairs, evacuation drills, and evacuation simulations and experiments had no clear relevance to transit speeds and times.

Participants' difficulties with the activity are shown in Figs. 8–10. Ten of the 13 participants indicated that pushing the wheelchairs was the most difficult part (Fig. 7). Ten of the 13 participants stated that it was "rather difficult" to perform the activity, which was the response option indicating the second-highest level of difficulty, although two participants indicated that it was "easy" and one chose the "usual" difficulty option (Fig. 8). Participants reported some muscle pain in the arm (n = 1) and lower back (n = 1), one said that they had experienced "backache" (n = 1), and 10 reported sufficient exertion to be "sweating." Nine subjects experienced shortness of breath (Fig. 9).

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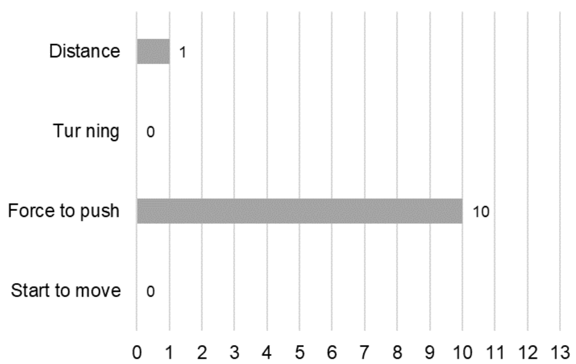

Figure 7. Aspects of the Difficulty of the Activity.

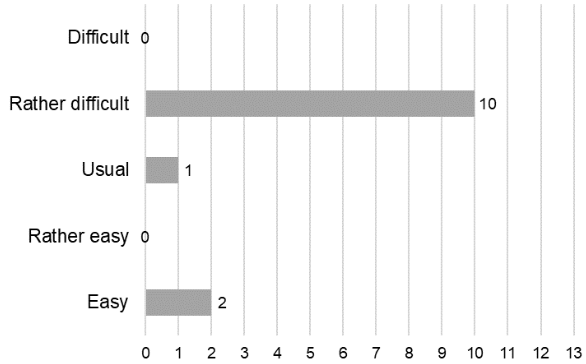

Figure 8. Extent of Physical Difficulty of the Activity.

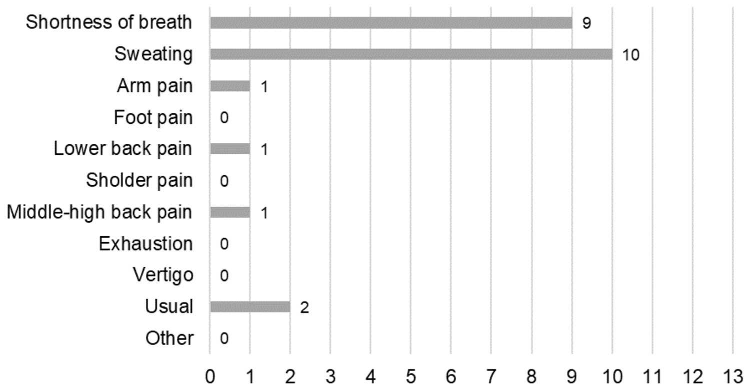

Figure 9. Effects on the Body of the Physical Activity (Multiple Responses Allowed).

4. DISCUSSION

There may be differences between the results obtained in this simulation and performance in a real disaster owing to differences in evacuation preparation time and doubts or indecision before starting to evacuate.

The average age of the participants differs from the average age of residents of this area. Therefore, these results may not fully reflect the transport speed and evacuee experiences on the day of a disaster. However, these findings are meaningful because this was a hands-on velocity experiment conducted along a real evacuation route, rather than a computer simulation. Therefore, the results could be used as realistic data for larger-scale computer-based evacuations. Future studies could further refine these data by asking residents to participate in an evacuation drill.

5. CONCLUSION

This study evaluated the feasibility of an evacuation route from a residential area to a designated destination for vulnerable people and caregivers. We conducted an experiment in Kainan City, Wakayama Prefecture, to simulate the evacuation of vulnerable people to the Minato Fureai Park. The key findings of this study are as follows.

The longest transit time was 3 min 54 s, the shortest transit time was 3 min 10 s, and the average was 3 min 25 s. The longest transit time to reach and pass Point 3 (as shown in Fig. 1), where the route left the predicted tsunami inundation zone, was 2 min 35 s, the shortest transit time was 1 min 56 s, and the average time was 2 min 15 s. Regarding the relationship between transit speed and gradient, speeds were slowest in Section 3, which had the steepest gradient. These results may be helpful in designing evacuation support plans to ensure the safety and wellbeing of residents in this and other areas at risk of tsunami damage. However, a limitation of the simulation was the small number of participants. Unlike previous simulations conducted in buildings or outdoors at private locations, this simulation used the streets that residents use daily. Therefore, the simulation had some spatial and temporal limitations. Future studies should carefully measure speed and other aspects of evacuee activity to reduce tsunami casualties.

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