Impacts of Water Depth on Pedestrian Speed, Gait, and Stability: results from an experimental study

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Abstract Evacuation and rescue operations during floods often necessitate walking in water. We conducted controlled experiments with 188 volunteers under four water depths (0 m, 0.35 m, 0.60 m, and 0.90 m) to analyze the effects of water depth on movement. These findings elucidate the impact of water depth on pedestrian dynamics, show gender-related correlations in this context, and provide critical insights into gait characteristics in varying water depths.

Keywords Flood evacuation, Evacuation experiment, Pedestrian dynamics, Walking speed, Gait characteristics

Introduction

In the context of emergency evacuations and rescue operations during flooding events, both affected individuals and rescuers frequently encounter the necessity of traversing through water. Consequently, a thorough understanding of pedestrian dynamics in flood environments is imperative for ensuring the safety of evacuees.

Researchers have undertaken individual pedestrian speed experiments in water tanks [1, 2] and swimming pools [3] featuring varying water depths. These experiments have demonstrated a substantial reduction in pedestrian movement speed in water compared to on land. Moreover, an exponential correlation between pedestrian speed and the specific flood force per unit width (derived from the combination of flood depth and speed) has been observed, indicating a decrease in pedestrian speed with increasing water depth. However, existing research has yet to reach consensus regarding the impact of gender on movement speed, and there remains a paucity of data on pedestrian gait characteristics.

To address this gap, we conducted experiments to examine pedestrian movement at four distinct water depths (0 m, 0.35 m, 0.60 m, and 0.90 m), representing no water, below-knee, above-knee, and waist-high water conditions. The objective was to elucidate the effects of gender and water depth on pedestrian speed, uncover gait characteristics at varying depths of water, and contribute richer data on the dynamics of pedestrian movement.

Experiments and Results

The experiments were carried out within a 1.8 m wide and 8 m long corridor built by guard poles. Figure 1 illustrates the experimental setup. We recruited 188 student volunteers (101 males and 87 females) to participate in our experiments. Before each trial, participants gathered on the left side of the *Start Line*. Upon the start signal, each volunteer began from the *Start Line*, simulating an emergency evacuation by proceeding quickly and safely through the *Measurement Area* to the *End Line*. To avoid interference, each volunteer was individually tested. After the current volunteer completed their traversal of the measurement area and left the corridor, the next volunteer would then begin their test.

A camera recorded the entire experiment. *PeTrack* software was used to calibrate the video, converting 2D pixel coordinates into real-world 3D coordinates. Pedestrian trajectories within the measurement area were extracted for data analysis.

We discussed the effects of water depth and gender on speed, quantified the pedestrian's lateral swaying amplitude, step frequency and step length by calculating the trajectory curvature, and introduced the coefficient of variation as a measure of the stability of step frequency and step length during walking. Our results indicate that water depth significantly affects pedestrian speed and gait characteristics: when

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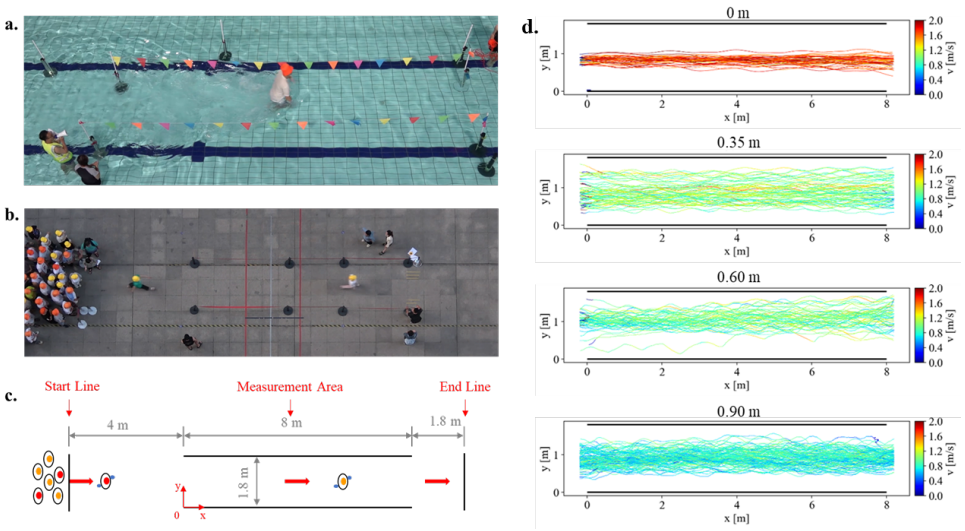

Figure 1: a). A video frame from the in-water experiment; b). A frame from the on-land (0 m depth) experiment; c). A schematic of the experimental layout. d). Pedestrian trajectories across different water depths, with the color bar indicating instantaneous speed. From top to bottom, the trajectories correspond to water depths of 0 m, 0.35 m, 0.60 m, and 0.90 m, respectively.

water depth increased from 0 m to 0.35 m, pedestrian speed declined significantly (by 38.6% for males and 44.8% for females), lateral swaying amplitude increased notably (69% in males and 133.3% in females), and step length shortened substantially (37.0% in males and 32% in females). Further increases in water depth, however, produced a diminishing effect on these measures. Furthermore, water presence accentuated gender differences in speed, while gender differences in step frequency, step length, and lateral swaying amplitude were primarily seen at 0 m depth. At water depths of up to 0.90 m, the Coefficients of Variation (CV) for step length and step frequency increased, suggesting reduced gait stability.

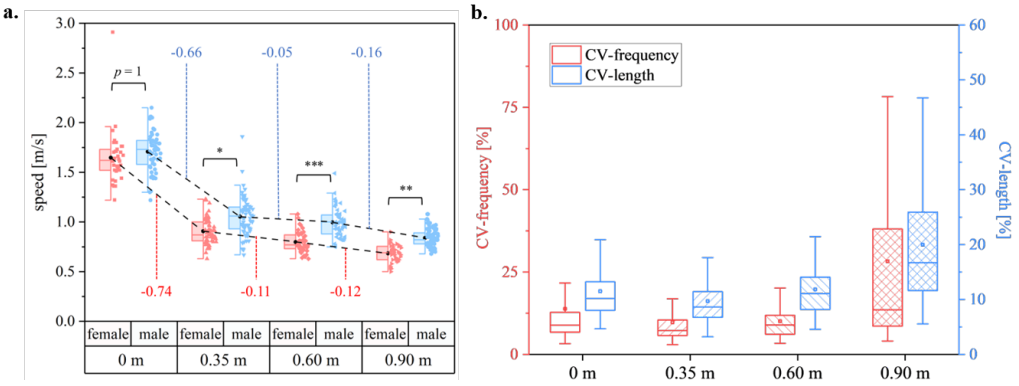

Figure 2: a). Boxplot of pedestrian movement speeds by gender across water depths,Dunn's post-hoc test significance markers are also included: *** for $p < 0.001$, ** for $p < 0.01$, and * for $p < 0.05$, denoting significant differences across water depths; b). Boxplots of coefficient of variation for step length and step frequency. The red box plot represents the coefficient of variation of step frequency, which corresponds to the left red axis, and the blue box plot represents the coefficient of variation of step length, which corresponds to the right blue axis.

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