Evacuation Behaviors of Wheelchair Users in a Right-angle Turn of the Width-limited Corridor

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Abstract: The evacuation characteristics of wheelchair users at the right-angle turn of a corridor were investigated experimentally with a focus on the effects of corridor width, wheelchair propulsion mode, and turning direction. The collision avoidance behaviors of two wheelchair users during the bidirectional encounters were also explored. Results indicate that corridor width shows influences on the evacuation performance of wheelchair users in the unidirectional experiments. In narrow corridors, wheelchair users exhibit longer trajectories, lower movement speeds, and higher absolute angular velocities, with the minimum speed occurring at the turn. Collisions with corridor boundaries become more frequent as width decreases, leading to abrupt speed drops and substantial directional adjustments. The pushing-assisted mode consistently yields shorter trajectories, higher movement speeds, and lower absolute angular velocities compared with the experiments under self-propelled mode, though this advantage diminishes in narrow corridors where width dominates the evacuation dynamics. In bidirectional evacuation experiments, inner-path wheelchair users typically yield to outer-path wheelchair users, resulting in lower speeds and, in some cases, longer evacuation times despite shorter trajectories. Collisions between opposing wheelchair users occur more frequently in pushing-assisted bidirectional experiments, whereas no collisions were observed under the self-propelled mode. These findings provide quantitative insights into the evacuation of wheelchair users in confined building corridors.

Key Words: Evacuation behavior; wheelchair users; right-angle turn; unidirectional evacuation; bidirectional evacuation; collision avoidance

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1. Introduction

Safety evacuation remains a core topic of continuous interest in the fields of safety science and emergency management. The safety evacuation of special populations, such as patients, the disabled, the elderly, and children, has received considerable attention due to their inherent physiological limitations in mobility. During emergency evacuations, these individuals often rely on wheelchairs as mobility aids. There are many differences between the evacuation process of wheelchairs and that of pedestrians, including the occupied space, the evacuation speed, and the physical condition requirements of evacuation paths. These differences affect the design standards of evacuation routes. Therefore, studies focused on the evacuation behaviors and speed characteristics of wheelchair users are crucial for developing targeted and effective evacuation strategies. The corridor is the main horizontal evacuation channel within buildings, and corridor turns are more likely to become bottlenecks, thereby posing potential risks, especially in emergencies. Therefore, studies on the evacuation behaviors of wheelchair users in corridor turns are necessary to develop a deeper understanding of the evacuation characteristics of wheelchair users and to contribute to the refinement of safety evacuation design in places such as hospitals and nursing homes.

Numerous studies have been conducted on safety evacuation and have addressed various aspects in

this field. A portion of these studies were conducted through experiments, including observation experiments [1-3] and laboratory-controlled experiments [4-7]. There were also a considerable number of simulation models established for investigating safety evacuation issues [8-11]. The scope of safety evacuation research comprises various domains, such as the evacuation characteristics of evacuees at typical locations on the evacuation route (e.g., exits, and staircases) [12-15]; the evacuation process in special places like ships and trains [16-19]; the impact of specific behaviors, such as group and detour behaviors, on the evacuation speed [20-22]; and the evacuation process under extreme conditions, such as fires and floods [1, 23-24].

Considerable attention has also been paid to the safe evacuation of vulnerable pedestrians, including young children, the elderly, and pedestrians with mobility impairments. Evacuation of children was investigated by Larusdottir et al. [25], Fang et al. [26], Najmanová et al. [27-29], and Feng et al. [30]. Based on these studies, it has been widely indicated that the evacuation characteristics of children differ significantly from those of adults. The average evacuation speed of children is generally lower than that of adults. However, children exhibit greater flexibility in crowded environments, enabling them to maintain a higher evacuation efficiency under high-density conditions. The evacuation speed of children was highly correlated with their age, with older children typically demonstrating higher speeds compared to younger children. In terms of the evacuation of the elderly, Ren et al. [31] conducted a comparative study on the movement characteristics of the elderly and young adults. They indicated that the fundamental diagram of the elderly and the young adults illustrated a similar trend, but the speed of the elderly was always lower than that of the young adults under the same density. Huang et al. [32] explored the walking speed of the elderly in a smoke-filled environment. They proposed a quantitative relationship between the walking speed of the elderly and the extinction coefficient of smoke. Liu et al. [33] developed an agent-based simulation model for the evacuation of older adults within elderly care facilities. They indicate that the optimal evacuation strategy is for nursing staff to first assist the disabled elderly under their responsibility and then search for and assist the nearest disabled elderly. In addition, they also explored the optimal spatial layout arrangement of the room for disabled elderly. The evacuation issues of pedestrians with mobility impairments were noticed by Kuligowski et al. [34], Lena et al. [35], and You et al. [36]. Their investigations show that the impaired pedestrians generally exhibit slower walking speeds during evacuations, and their presence can also contribute to the decrease in evacuation efficiency of the entire crowd.

For pedestrians with mobility impairments, the assistance of movement is essential. Relevant investigations have been conducted, covering measures such as assistance by others [37], the use of crutches [38], and taking elevators [39]. Among various assisted evacuation methods, the use of wheelchairs is one of the most frequently observed methods in practice; therefore, the study on evacuation characteristics of wheelchair users is important and necessary. Experiments on evacuation flow of crowds, including wheelchair users were conducted by Shimada et al. [40]. They indicated that the pedestrian flow rate at the exit decreased as the number of wheelchair users in the crowd increased. Feliciani et al. [41] conducted an evacuation experiment of a crowd including normal pedestrians and wheelchair users to explore the influence of exit information that is received by the pedestrians on the evacuation time of the crowd. They claimed that whether the wheelchair users were informed of the exit location in advance could significantly reduce the evacuation time. Pan et al. [42] conducted a series of experiments in a straight corridor that focused on the evacuation process of a mixed crowd with both normal individuals and wheelchair users. They found that the presence of wheelchair users decreased the density range and flow rate of the pedestrian flow and increased the critical headway and

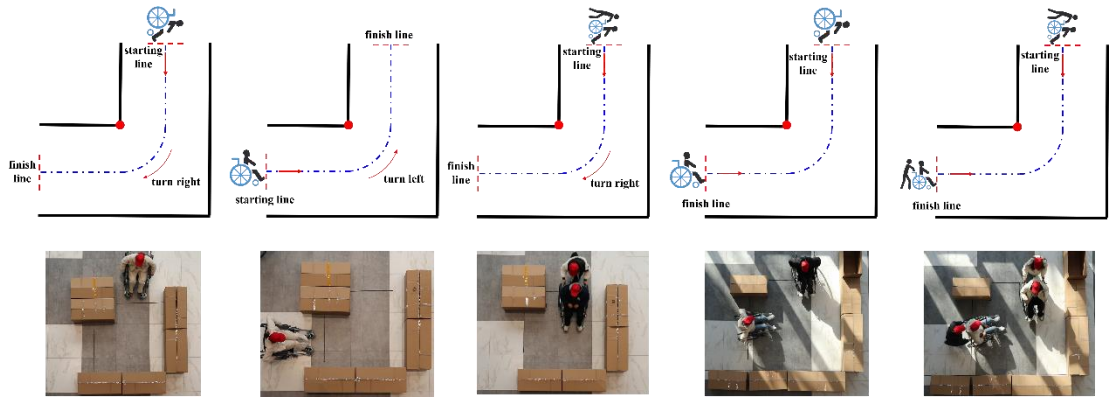
safe response time. An experimental study on the evacuation dynamics of a mixed crowd, in which wheelchair users were included, was conducted by Fu et al. [43]. They found that the presence of disabilities had an adverse effect on the evacuation of the crowd, resulting in an increase in the evacuation time and more danger. The evacuation dynamics of a heterogeneous crowd with normal pedestrians and pedestrians with different types of disabilities were explored by You et al. [36, 44]. The heterogeneous crowd included six types of disabled individuals, among whom were wheelchair users. Compared with other disabled individuals, the wheelchair user had the smallest average offset distance, as well as the global velocity, and the area occupied by the wheelchair user was the largest. The proportion of wheelchair users significantly affects the evacuation dynamics of the heterogeneous crowd; a higher proportion of wheelchair users requires larger safety distances among pedestrians in the heterogeneous crowd. The exit width had a significant influence on the evacuation efficiency of wheelchair users. Smedberg et al. [45] explored the influences of wheelchair users on the exit choice decisions of neighboring evacuees through virtual reality experiments, and a mixed-logic model was established based on the experimental results. They found that the choice of exit by participants during experiments was influenced by the exit choice decision of neighboring evacuees, and this influence was more significant when the neighboring evacuee was a wheelchair user.

To sum up, in the above studies related to the evacuation of wheelchair users, the attention has primarily been paid to the mixed crowd that includes wheelchair users, and the associated experiments have mostly been conducted in straight corridors. However, studies dedicated specifically to the evacuation behavior of wheelchair users themselves, especially in structurally complex environments, remain limited. Therefore, the evacuation experiments on wheelchair users were conducted at the right-angle turn of a corridor in the present study. The evacuation characteristics of wheelchair users and the collision avoidance behaviors of two opposite wheelchair users in the right-angle turn under different corridor widths, wheelchair propulsion modes, and turn directions were mainly focused on.

2. Experimental setting and scenario design

2.1 Experimental setting

The wheelchair evacuation experiment was conducted in a three-story atrium of an office building at a university, with permission from the administrator. The layout of the experimental site in different scenarios is shown in Figure 1. Two types of evacuation experiments were conducted: unidirectional evacuation experiment and bidirectional evacuation experiment of the wheelchair users. In the unidirectional evacuation experiments, as shown in Figure 1 (a), (b), and (c), the overall dimensions of the experimental area are 2 m × 2 m. In the bidirectional evacuation experiments, as shown in Figure 1 (d) and (e), the overall dimensions of the experimental area are 2.5 m × 2.5 m. The corridor turns of different widths in each scenario were created by using cardboard boxes as partitions. These boxes were filled with counterweights to ensure their stability during experiments. Under conditions with different corridor widths, the distance from the turning point to the boundary of the experimental area varies, i.e., the traveling distance of wheelchair users from the start to the beginning of the turn differs. Compared with the turning process, the evacuation speed of wheelchair users during this straight segment is relatively higher. To enable a more reasonable comparison of the evacuation processes of the wheelchair users across different width conditions, when analyzing speed-related parameters, the start and end points for each condition were set at 0.5 m from the turning point, as indicated by the black tape on the floor in Figure 1.



(a) Scenario A-R (b) Scenario A-L (c) Scenario B-R (d) Scenario C-B (e) Scenario D-B

Figure 1 Layout of the experimental site in different scenarios

The same type of wheelchair was used in all experiments with the parameters listed in Table 1. A video camera (25 frames per second) was mounted in the third-floor corridor of the atrium (ground elevation) to record the experimental process. The installation height was approximately 12 meters above ground level. To get the pedestrian trajectories from the video, the cameras were oriented almost perpendicular to the ground plane. A total of 24 university students participated in the wheelchair evacuation experiments. The information of participants' age, height, weight, and dominant hand is listed in Table 1. Prior to the experiment, all participants were fully informed of the experimental procedures and safety precautions. Sufficient familiarization time was provided for participants to practice using wheelchairs prior to the experiments, since they were not regular wheelchair users. Four wheelchairs of the same model with a width of 70 cm were used in the experiments. The wheelchairs can be operated in two modes: self-propelled mode or pushing-assisted mode. Under the self-propelled mode, the wheelchair users evacuate by propelling the wheelchair themselves. Under the pushing-assisted mode, the wheelchair users remained seated in the wheelchairs and were pushed by an assistant. Under this mode, the wheelchair users did not steer the wheelchair or give any instructions; both the direction and speed of their movement were entirely controlled by the assistant. The detailed parameters of the wheelchair are listed in Table 1.

Table 1 Summary of experimental parameters

Ambient conditions			Indoor environment, Temperature:15 ºC, Humidity:40%
Participants	Total number		24
	Age		20~22
	Height/ cm	Standing	Mean ± SD: 169.8 ± 6.0; Range: 160~178
		Sitting	Mean ± SD: 91.3 ± 2.9; Range: 85~96
	Weight/ kg		Mean ± SD: 62.8 ± 8.7; Range: 50~80
	Dominant hand		Right hand: 92%; Left hand: 8%
Wheelchair	Width/ cm		70
	Height of the seat/ cm		45
	Diameter of the wheel/ cm		60
	Mode		Self-propelled/pushing-assisted

The moving trajectory, i.e., the X and Y coordinates of each frame of all participants, was extracted based on the video recordings using the PeTrack [46]. For the convenience of extracting the movement trajectories of participants from the video by using the PeTrack software, all participants in the experiment were equipped with red hats, and they were reminded to keep their heads as stationary as possible and to avoid unnecessary lateral head movements, tilting, or nodding, even when a collision occurred. This was to ensure that the hat of wheelchair users, which was the tracking marker for trajectory extraction, did not deviate significantly from its initial position relative to the wheelchair. Based on the moving trajectory of wheelchair users, the instantaneous movement $v(t)$ and absolute angular speed $|\omega(t)|$ were computed. Let $\mathbf{r}(t)=[x(t), y(t)]$ denote the planar position of the wheelchair user, traced by the red hat at time t. Let $\theta(t)$ denote the orientation angle of the wheelchair user, measured with respect to the global x-axis, at time t. Then, by using the central difference method, the instantaneous movement speed and absolute angular speed are given by

$$v(t)=\frac{\sqrt{[x(t+1)-x(t-1)]^2+[y(t+1)-y(t-1)]^2}}{2\Delta t} \tag{1}$$

$$|\omega(t)|=\frac{|\theta(t+1)-\theta(t-1)|}{2\Delta t} \tag{2}$$

The orientation angle of the wheelchair user at time t was given by

$$\theta(t)=atna2[v_x(t),v_y(t)]=atna2\left(\frac{x(t+1)-x(t-1)}{2\Delta t},\frac{y(t+1)-y(t-1)}{2\Delta t}\right) \tag{3}$$

where $v_x(t)$ and $v_y(t)$ denote the velocity components of the wheelchair user in the X and Y directions at time t, respectively. Both quantities were evaluated at each sampling time step Δt, which is valued as 0.04 s in this study.

2.2 Scenario design

The experimental scenarios are shown in **错误!不能识别的开关参数。**. There were four major types of experiments conducted, and labeled as Test A, B, C, and D. Test A was the self-propelled evacuation experiments as shown in **错误!不能识别的开关参数。** (a) and (b), and the right-angle turn conditions with five corridor widths and the left-turn conditions with three corridor widths were conducted, respectively. Test B was the pushing-assisted evacuation experiments as shown in **错误!不能识别的开关参数。** (c), and the right-angle turn conditions with five different corridor widths were conducted. Test C was the self-propelled evacuation experiment with two opposite wheelchair users, and Test D was the pushing-assisted evacuation experiment with two opposite wheelchair users, as shown in **错误!不能识别的开关参数。** (d) and (e), respectively. There were three scenarios with different corridor widths in Tests C and D. For all scenarios, the experiments were repeated ten times with different participants; therefore, the total number of experiments was 190 in the present study. In pushing-assisted evacuation experiments (Test B and Test D), the ten groups of assistant-wheelchair pairs were randomly assigned, and this pairing remained consistent across all conditions to enhance the comparability of the results. It should be noted that the unrestricted-width condition refers to the scenario where no obstructions are placed on the inner side of the turning corridor. Under these conditions, the wheelchair users performed the evacuation experiments within a square experimental area of either 2.0 m (unidirectional evacuation experiments) or 2.5 m (bidirectional evacuation experiments) in side length.

Table 2 Experimental scenarios

Test No.	Experimental description	Number of participants per experiment	Turn direction	Corridor width (l)	Number of experiments per scenario
A-R-1	Test A: Unidirectional evacuation; Self-propelled mode	One wheelchair user	Right turn	1.0 m	10
A-R-2				1.1 m	10
A-R-3				1.2 m	10
A-R-4				1.4 m	10
A-R-5				Unrestricted	10
A-L-1			Left turn	1.0 m	10
A-L-2				1.1 m	10
A-L-3				Unrestricted	10
B-R-1	Test B: Unidirectional evacuation; Pushing-assisted mode	One wheelchair user + one pushing assistant	Right turn	1.0 m	10
B-R-2				1.1 m	10
B-R-3				1.2 m	10
B-R-4				1.4 m	10
B-R-5				Unrestricted	10
C-B-1	Test C: Bidirectional evacuation; Self-propelled mode	Two wheelchair users	Bidirectional	1.8 m	10
C-B-2				2.0 m	10
C-B-3				Unrestricted	10
D-B-1	Test D: Bidirectional evacuation; Pushing-assisted mode	Two wheelchair users + two pushing assistants	Bidirectional	1.8 m	10
D-B-2				2.0 m	10
D-B-3				Unrestricted	10

Prior to the experiments, all the wheelchair users and their assisting personnel (if the experiment required) were positioned at the center point of the corridor entrance. Participants were instructed to traverse the experimental area as quickly as possible while adhering to safety protocols for themselves and others. In the event of collisions with other participants or corridor boundaries, the participant was required to promptly adjust their movement direction and continue completing the experiment. In the bidirectional evacuation experiments (Test C and D), the avoiding behaviors of the wheelchair users were determined by themselves based on the specific circumstances.

3. Evacuation process of wheelchair users in L-shaped turns

3.1 Self-propelled evacuation process under different widths

Under the right-turn condition, the movement trajectories of participants in corridors with widths of 1.0 m, 1.1 m, 1.2 m, 1.4 m, and the unrestricted width are illustrated in **错误!未找到引用源。**. Across all the scenarios, the movement speed of wheelchair users exhibited a pattern of being comparatively higher upon entering and exiting the corridor and showed the lowest speeds in the central turning area, which was mainly attributed to the necessary speed reduction for directional adjustments. In the narrow corridor conditions, the directional adjustment of the wheelchair users was difficult since they had to avoid collisions with the corridor boundaries in the meantime. In the 1.0-meter corridor condition, some wheelchair users even showed step-back behaviors during the experiment, as shown in **错误!未找到引用源。**. Therefore, as the corridor width increases, the movement speed of wheelchair users through the entire experimental area showed a corresponding increase. The trajectory shape of the wheelchair users was also affected by the corridor width. In the narrow corridor conditions, wheelchair

users have limited turning space, resulting in a smaller turning radius and a longer travel distance.

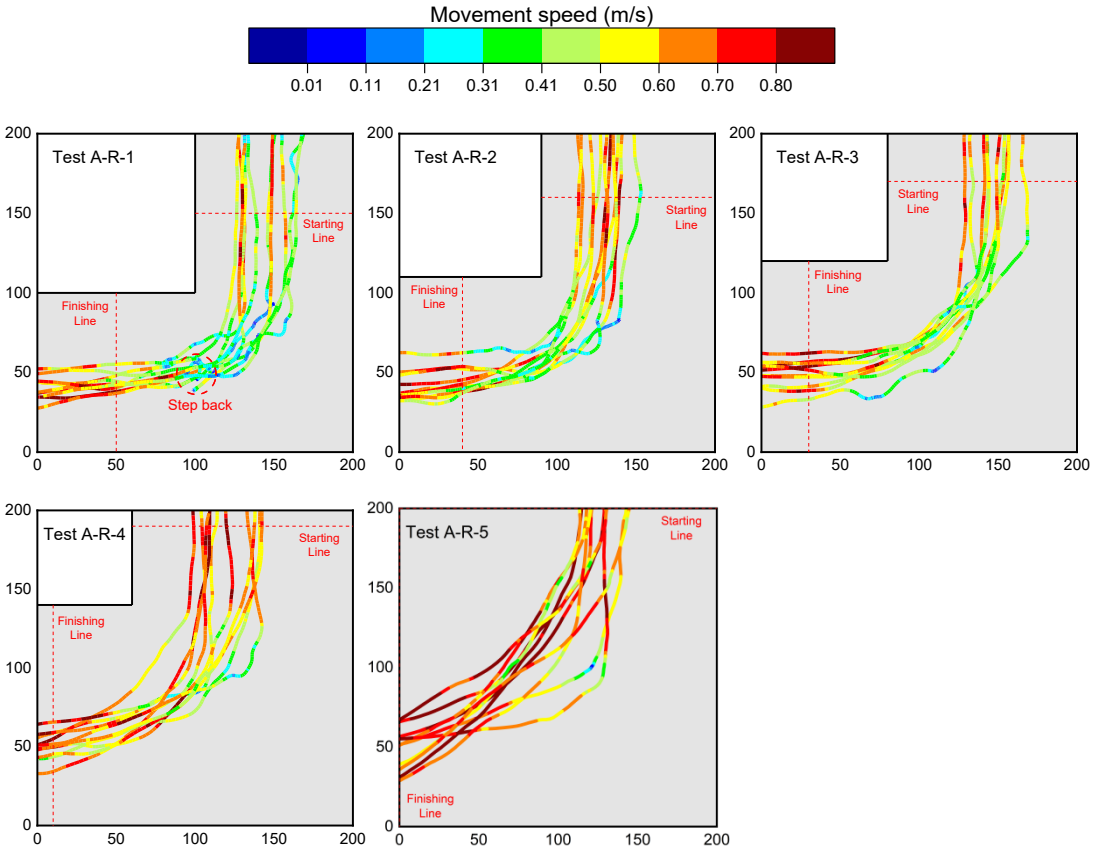


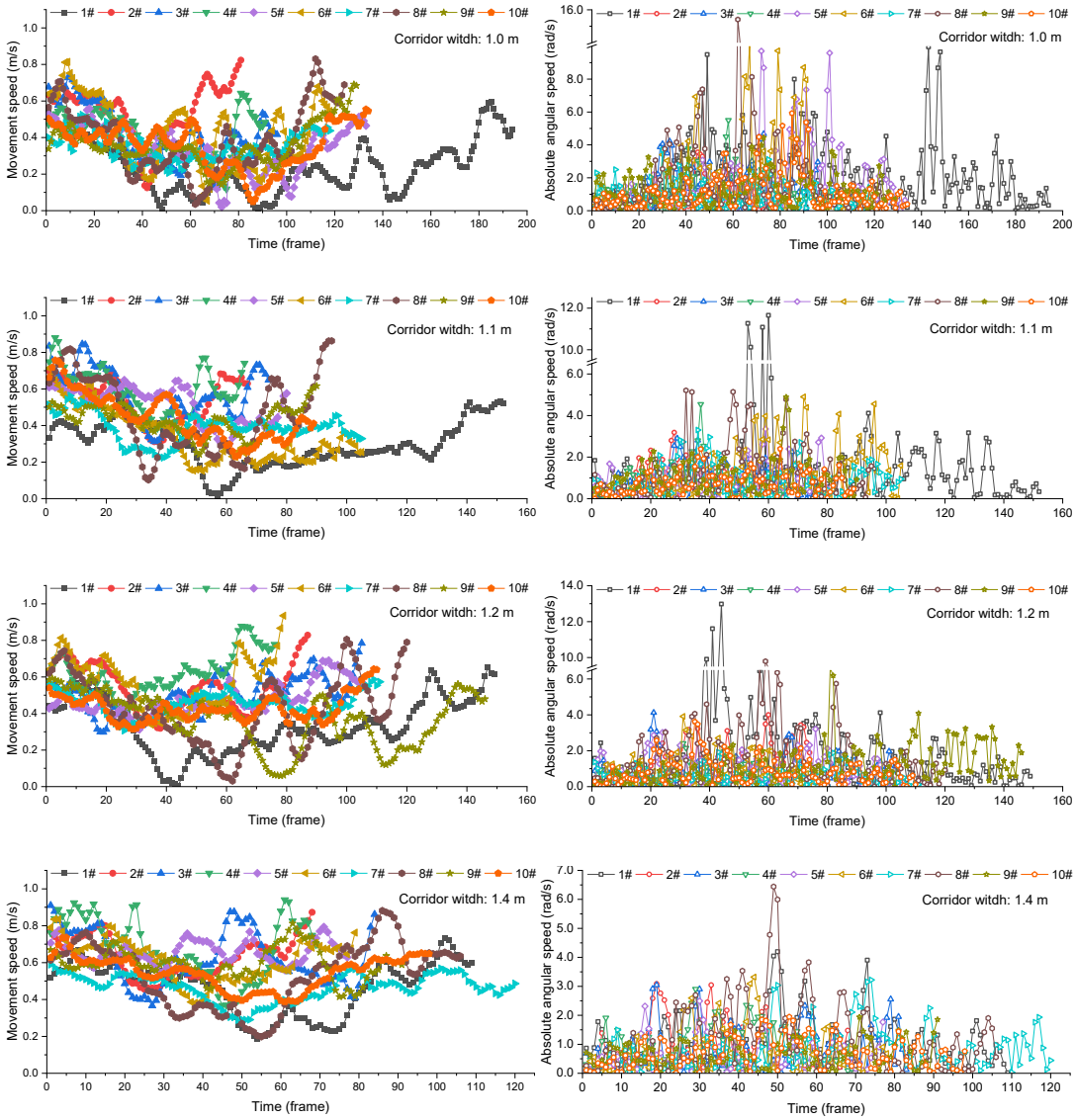
Figure 2 Movement trajectories and movement speeds of wheelchair users in Test A-R-1~5

The instantaneous movement speed and absolute angular speed for all participants in Test A-R with different corridor widths are shown in Figure 3. The movement speed of wheelchair users generally increased with corridor widths. Except for the unrestricted corridor conditions, the movement speed of wheelchair users decreases as they approach the turning point in all other conditions, and their movement speeds reach the minimum during the turning process. Taking all ten participants into account, the average values of the minimum speed in scenarios with corridor widths of 1.0 m, 1.1 m, 1.2 m, and 1.4 m are 0.088, 0.223, 0.240, and 0.359 m/s, respectively. The narrower the corridor, the greater the reduction in movement speed during turning. After the turning, the movement speed of wheelchair users progressively increased. In unrestricted corridor conditions, the fluctuations of movement speed were still present, while the turning-induced speed variation pattern (the movement speed decrease and then recovery) was not obvious.

The absolute angular speed of wheelchair users in Test A-R-1~5 is also illustrated in Figure 3. Overall, the smaller the corridor width, the greater the absolute angular speed of wheelchair users during their passage. When the corridor width was 1.0 m, the maximum absolute angular speed of wheelchair users was 15.4 rad/s, whereas when the corridor width increased to 1.4 m, the peak absolute angular speed decreased to 6.4 rad/s. This is because wheelchair users have a higher probability of colliding with the corridor boundaries under the narrow corridor conditions. Once the collision occurs, not only does their movement speed decrease, but a substantial directional adjustment is also required to continue moving forward, leading to an increase in angular speed. In addition, in narrower corridors,

wheelchair users tend to make adjustments to their moving direction more frequently in order to avoid collisions with the corridor boundaries. The absolute angular speed of wheelchair users exhibited only small fluctuations when entering the corridor and after completing the turning process, but the fluctuations became severe during the turning process. The increasing phase of the absolute angular speed corresponded exactly to the decreasing phase of their movement speed.

According to 错误!不能识别的开关参数。, the movement speed of wheelchair users was critically low at certain moments, approaching or even dropping below 0.1 m/s, when the corridor widths were 1.0, 1.1, and 1.2 m. In most cases, such extremely low movement speeds correspond to situations where wheelchair users have collided with the corridor boundaries. A collision of the wheelchair users typically resulted in a brief pause, followed by a quick, slight reversal for directional adjustment to complete the turning. The experimental results confirmed that narrower corridors led to more frequent collisions between the wheelchair users and the corridor boundaries.



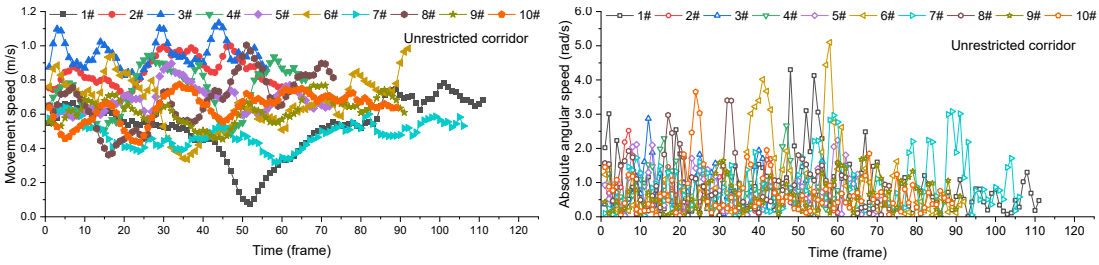


Figure 3 Movement speed and absolute angular speed of wheelchair users in Test A-R-1~5

To comprehensively compare the data of all participants under different corridor width conditions, the distributions, means, and standard deviations (SD) of the trajectory length, time-averaged movement speed, and time-averaged absolute angular speed of wheelchair users under each condition were presented in Table 3. It should be particularly noted that the time-averaged movement speed and absolute angular velocity of wheelchair users listed in the table were calculated based on the starting and finishing lines shown in Figure 2, whereas the trajectory length was calculated over the entire 2 m × 2 m area to facilitate comparison of data across all conditions. According to Table 3, the trajectory length and the absolute angular velocity of wheelchair users decreased, and the movement speed of wheelchair users increased with corridor width, which is consistent with the conclusions analyzed above.

In the unrestricted corridor condition, wheelchair users performed the right-angle turn process within a 2 m × 2 m open square area, so their movement speed was close to the turning speed under free-flow conditions. Therefore, taking the trajectory length, movement speed, and absolute angular velocity in the unrestricted condition as references, the ratios of the mean values of these three parameters under different corridor widths to those under the reference condition are shown in Figure 4. In the narrowest corridor condition, the trajectory length of the wheelchair users during the turning was 1.37 times and the absolute angular velocity was 1.74 times to those in the unrestricted condition. When the corridor widths were 1.1 and 1.2 m, the ratio of trajectory length and absolute angular velocity to those in the unrestricted corridor condition was about 1.2 to 1.3. When the corridor width increased to 1.4 m, the above parameters were close to those in unrestricted corridor conditions. The narrower the corridor, the more difficult it is for wheelchair users to traverse it, requiring frequent stopping and directional adjustments. Consequently, as the absolute angular velocity increases, the movement speed of wheelchair users decreases. In the conditions with corridor widths of 1.0, 1.1, 1.2, and 1.4 m, the ratios of movement speed to that in the unrestricted corridor condition were 0.56, 0.67, 0.69, and 0.85, respectively.

Table 3 Trajectory length, time-averaged movement speed, and time-averaged absolute angular speed in Scenario A-R

Corridor width	Trajectory length, L (m)			Time-averaged movement speed, $\bar{v}$ (m/s)			Time-averaged absolute angular speed, $\overline{\lvert\omega\rvert}$ (rad/s)		
	Range	Mean	SD	Range	Mean	SD	Range	Mean	SD
1.0 m	2.64~3.29	2.941	0.176	0.24~0.55	0.385	0.075	0.75~2.01	1.399	0.423
1.1 m	2.33~2.73	2.526	0.122	0.30~0.59	0.459	0.093	0.74~1.34	1.018	0.207
1.2 m	2.41~2.75	2.584	0.100	0.33~0.63	0.473	0.087	0.58~1.68	1.076	0.346
1.4 m	1.93~2.49	2.255	0.165	0.47~0.68	0.582	0.071	0.62~1.23	0.863	0.177
Unrestricted	1.95~2.45	2.145	0.166	0.48~0.95	0.684	0.132	0.63~0.96	0.802	0.122

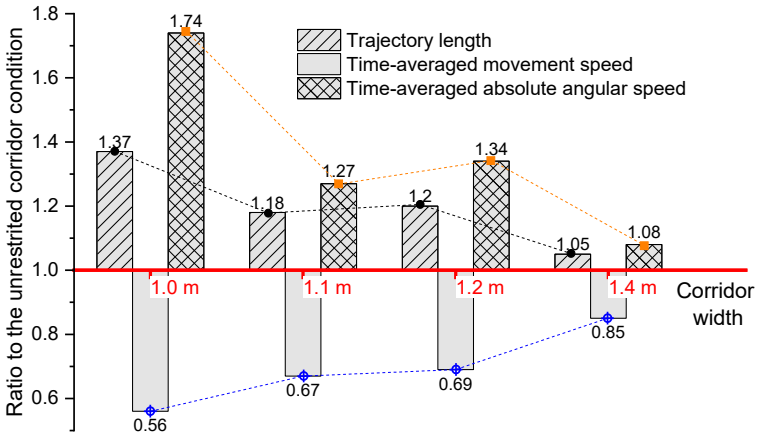
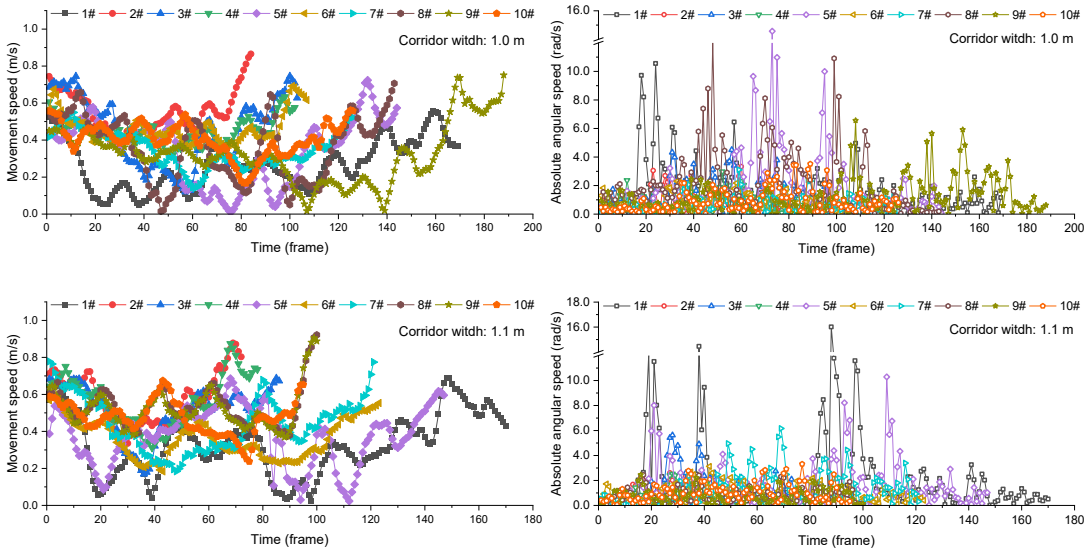


Figure 4 Ratio of the trajectory length, movement speed, and absolute angular speed in conditions with different corridor widths to those in the unrestricted corridor condition

By comparing the experiment results in Scenario A-R with those in Scenario A-L, the influences of turning direction on the evacuation process were also explored in the present study. The instantaneous movement speed and absolute angular speed for all participants in the left-turn condition with the 1.0 m, 1.1 m, and unrestricted corridor are shown in Figure 5, and the trajectory length, time-mean speed, and time-averaged absolute angular speed in the right-turn and left-turn conditions are summarized in Table 4. Although more than 90% of the participants were right-handed, no significant differences were observed in the trajectory length, movement speed, or absolute angular speed of wheelchair users between the left-turn and right-turn evacuation experiments based on Figure 5 and Table 4. This may be due to the low-friction tiled floor and the fact that all participants were young adults, both of which enabled the pushing force with either the right hand or left hand of the wheelchair users to be sufficient for propelling the wheelchair forward. According to Table 4, the number of collisions between wheelchair users and the corridor boundaries in the right-angle turn condition is slightly higher than that in the left-turn condition. This may be because when turning left, wheelchair users mainly use their right hand to control the movement direction, and since more than 90% of the participants are right-handed, their directional control is more precise.



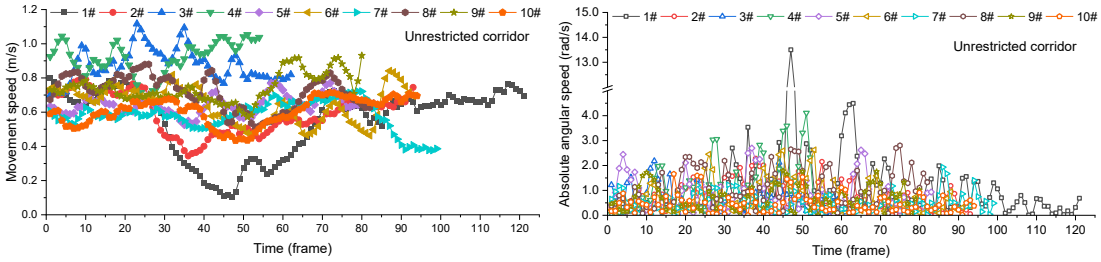


Figure 5 Movement speed and absolute angular speed of wheelchair users in Test A-L-1~3

Table 4 Comparison of the trajectory length, time-mean speed, and time-averaged absolute angular speed between the right-turn and the left-turn conditions

Evacuation parameters		1.0 m corridor	1.1 m corridor	Unrestricted corridor
Trajectory length, L (m)	Right turn	2.941	2.526	2.145
	Left turn	2.943	2.741	2.259
Time-averaged movement speed, $\bar{v}$ (m/s)	Right turn	0.385	0.459	0.684
	Left turn	0.397	0.47	0.687
Time-averaged absolute angular speed, $\overline{\lvert\omega\rvert}$ (rad/s)	Right turn	1.399	1.018	0.802
	Left turn	1.157	1.12	0.8
Number of collisions	Right turn	3	1	0
	Left turn	1	1	0

3.2 Pushing-assisted evacuation process under different widths

Wheelchairs typically have two modes of propulsion: the wheelchair users evacuate by propelling the wheelchair themselves or being pushed by an assistant. To analyze the difference in evacuation speeds between the above two propulsion modes of wheelchairs, a comparative analysis of scenarios A-R and B-R was conducted. Movement speed and absolute angular speed of wheelchair users pushed by an assistant are illustrated in Figure 6. Compared with Figure 3, under the pushing-assisted mode, the movement speed of wheelchair users was higher, and the absolute angular speed of wheelchair users was lower than those of the self-propelled wheelchair users. This indicates that directional control of the wheelchair is more precise and that it is easier to exert propulsive force under the pushing-assisted mode.

With an increase in corridor width, the movement speed of the pushing-assisted wheelchair users increased, and the absolute angular speed of the pushing-assisted wheelchair users decreased basically. In narrow corridor conditions with corridor widths of 1.0 m and 1.1 m, the movement speed of wheelchair users that are pushed by others first decreases and then increases, with the lowest speed occurring at the turn, while the absolute angular speed shows an obvious increase at the turn. These trends are consistent with those observed for conditions of self-propelled wheelchair users. However, when the corridor width reaches 1.2 m or above, the temporal variation patterns of the movement speed and absolute angular speed of the pushing-assisted wheelchair users change. Under such conditions, the absolute angular speed of the pushing-assisted wheelchair users fluctuates within a stable range, while their movement speed shows a continuously increasing trend. To better illustrate the above variation patterns, the trajectories and movement speeds of pushing-assisted wheelchair users under the corridor width conditions of 1.1 m and 1.4 m are shown in Figure 7. It indicates that in wider corridors, turning does not have a significant influence on the evacuation process of the pushing-assisted wheelchair

users, and the corridor width is the primary factor restricting the speed of the pushing-assisted wheelchair users.

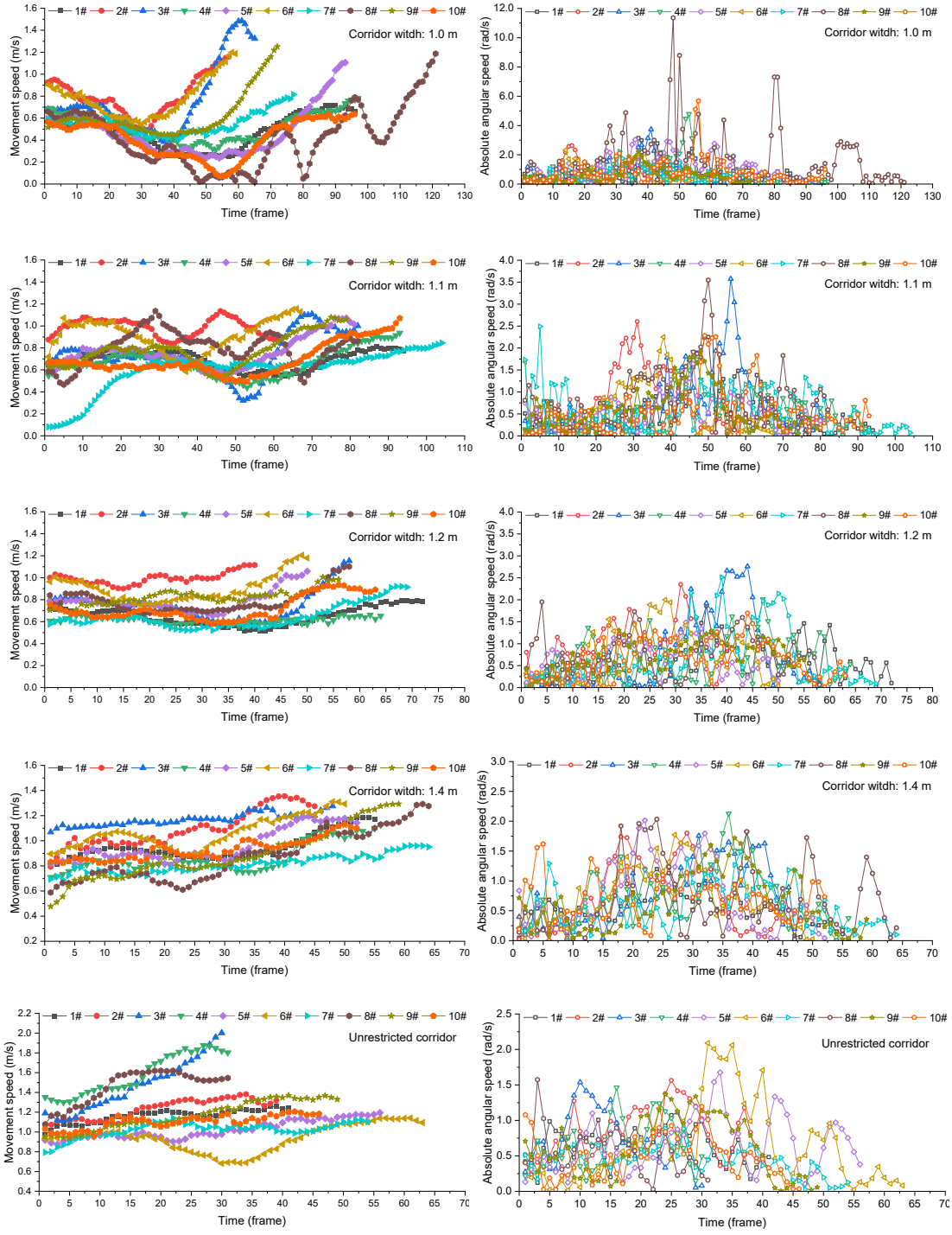


Figure 6 Movement speed and absolute angular speed of wheelchair users in Test B-R-1~5

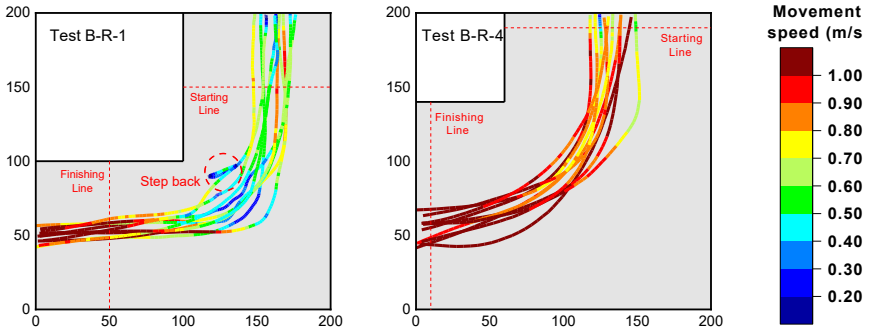
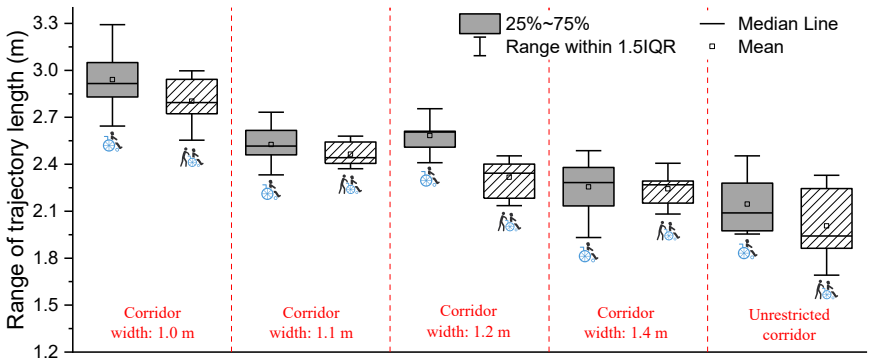


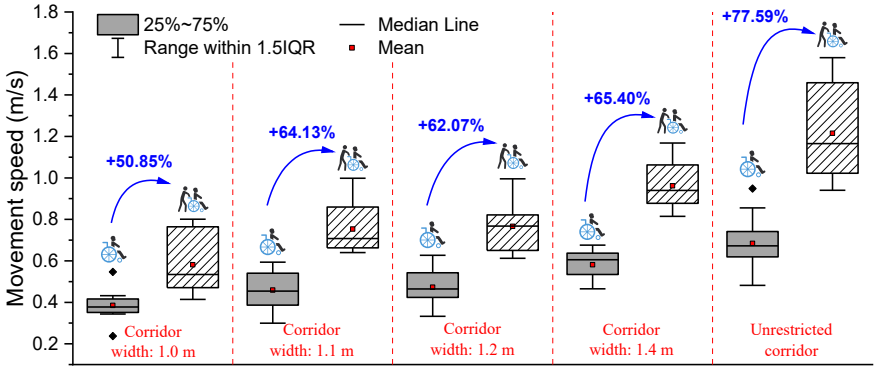
Figure 7 Movement trajectories and movement speeds of pushing-assisted wheelchair users in Test B-R-1 and Test B-R-4

Comparisons of trajectory length, time-mean movement speed, and time-averaged absolute angular speed of wheelchair users under the self-propelled mode and pushing-assisted mode are illustrated in Figure 8. The variation patterns of the three evacuation parameters of wheelchair users—trajectory length, movement speed, and absolute angular speed—are consistent with those observed in the self-propelled wheelchair condition.

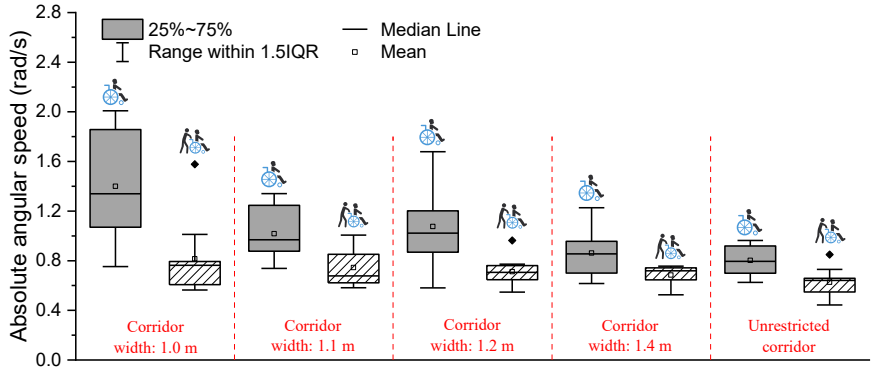
Comparing the three evacuation parameters between the two modes, based on the statistical means, the trajectory length of wheelchair users under the pushing-assisted mode is shorter than that in the self-propelled conditions under all corridor width conditions. The time-averaged absolute angular speed of pushing-assisted wheelchair users is also lower than that in the self-propelled wheelchair conditions. In the pushing-assisted wheelchair condition, collisions with the corridor boundaries occurred once at the narrowest corridor. Under the pushing-assisted condition, the number of collisions between wheelchair users and corridor boundaries was lower than that under the self-propelled condition. Based on Figure 8(b), the movement speeds of wheelchair users under the pushing-assisted mode are obviously higher than those under self-propelled mode. Meanwhile, compared to the self-propelled condition, the degree of dispersion of the movement speed of wheelchair users under pushing-assisted mode is higher. Taking the mean value as the comparative parameter, the movement speed of wheelchair users under the pushing-assisted condition is 50.85% to 77.59% higher than that under the self-propelled condition. Among the five corridor widths analyzed in this study, the percentage increase in movement speed of pushing-assisted wheelchair users increases with corridor width, which indicates that the advantage of the pushing-assisted mode in enhancing the evacuation speed of wheelchair users grows with increasing corridor width.



(a) Trajectory length



(b) Movement speed



(c) Absolute angular speed

Figure 8 Comparison of the trajectory length, time-mean speed, and time-averaged absolute angular speed of wheelchair users between the self-propelled and pushing-assisted modes

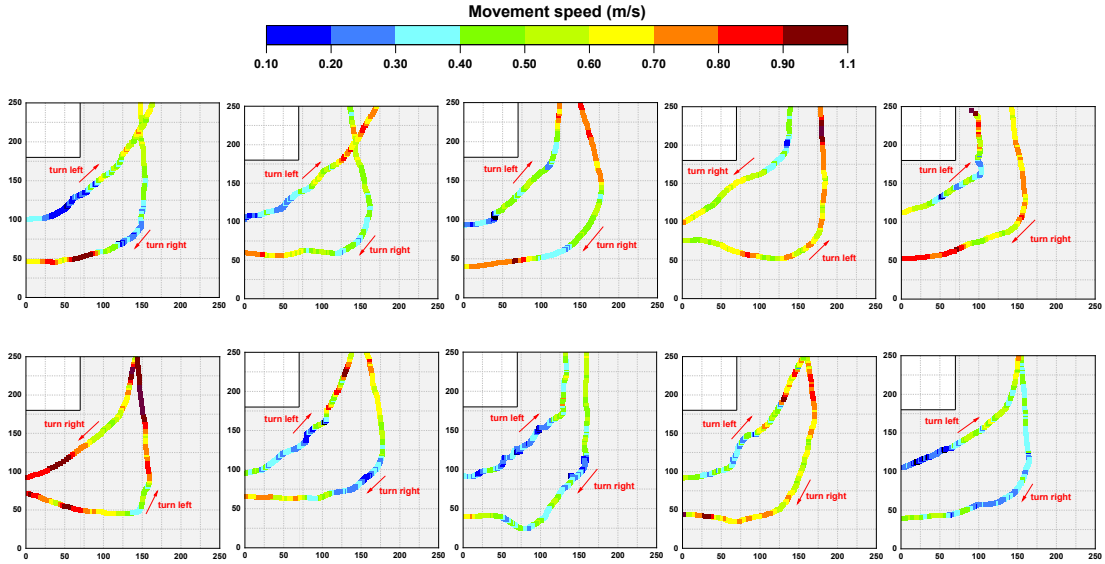
4. Bidirectional evacuation of wheelchair users in L-shaped corridor turns

4.1 Bidirectional evacuation of wheelchair users under self-propelled mode

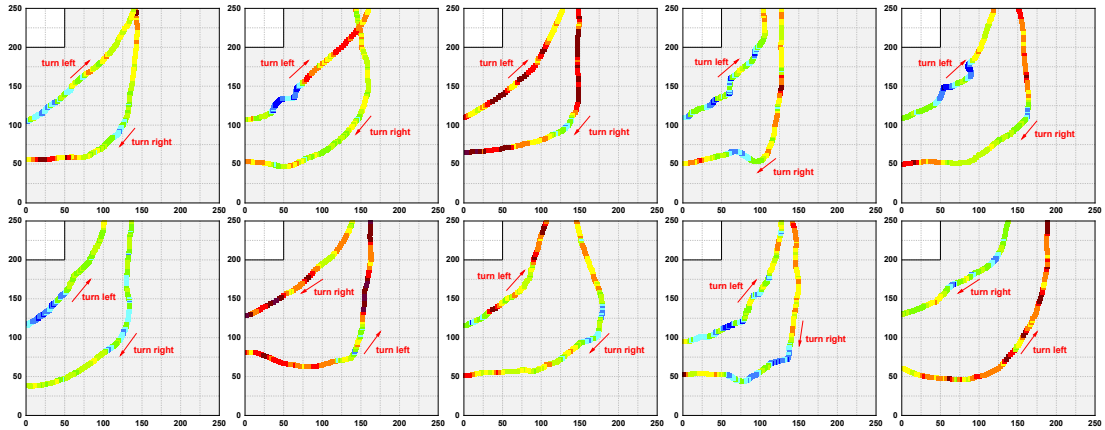
The avoidance behaviors and evacuation processes of two self-propelled wheelchair users in opposing directional encounters at the turning areas were discussed. The trajectories and movement speeds of each group of wheelchair users during bidirectional evacuation under the self-propelled mode are shown in Figure 9. The two wheelchair users in opposing directions are usually separated into inner and outer paths to prevent conflicts, and a speed reduction is also observed during the interlaced turning process. Under the restricted corridor width conditions, the wheelchair users on the inner and outer paths cannot pass simultaneously side by side. For most experiments, particularly under width-restricted scenarios, the movement speeds of the inner- and outer-path wheelchair users follow the same pattern as in the unidirectional evacuation experiments: they travel faster when entering and exiting the corridor, and slower at the right-angle turn. Compared with the results of unidirectional evacuation experiments of wheelchair users, it can also be observed that in the bidirectional evacuation experiments, the dispersion of the movement speed data of the ten groups of wheelchair users in the same experimental scenario is higher. This is mainly because, in the bidirectional evacuation experiments, the movement speed of a wheelchair user depends not only on the individual and the experimental site but also on the trajectories and conflict-avoidance decisions of the opposing wheelchair user.

Regarding the choice of the inner or outer side for getting through the right-angle turn corridor, no assignment or guidance was given to the wheelchair users on both sides before the experiments; it was determined by the participants themselves. However, it was found that in the majority of experiments

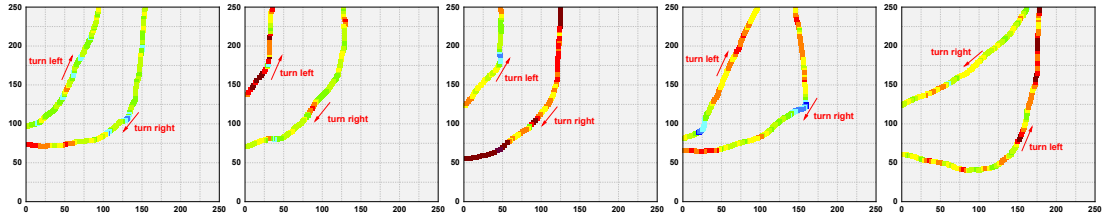
(80% for the 1.8 m corridor scenario, 80% for the 2.0 m corridor scenario, and 90% for the unrestricted corridor scenario), the left-turn pedestrians chose to pass on the inner side, while the right-turn pedestrians chose to pass on the outer side. One major possible reason for this phenomenon is that the first group of participants chose the left-turn wheelchair users to pass on the inner side and the right-turn ones on the outer side. Subsequent participants then adopted the same conflict-avoidance pattern due to the learning effect. In addition, during the brief oral interviews after the experiments, some participants reported that their choice of the inner or outer side during the experiments was related to their dominant hand. Most participants in the present experiments were right-handed. At the beginning of the experiment, the stronger exertion of force was from the dominant hand, which resulted in a left-turn tendency of the wheelchair, as illustrated in Figure 10. This consequently led to left-turn wheelchair users choosing the inner side and right-turn wheelchair users choosing the outer side.

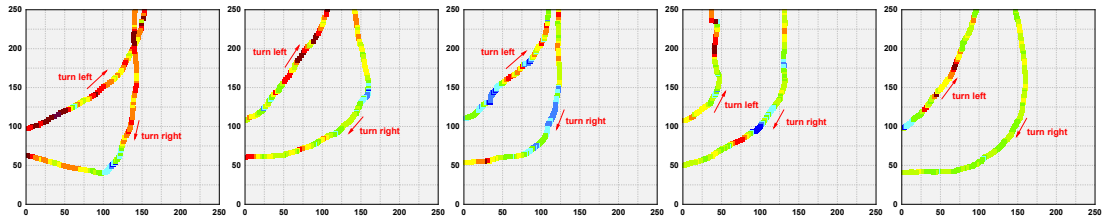


(a) Test C-B-1



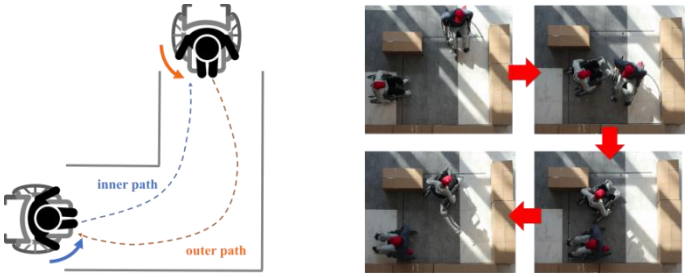
(b) Test C-B-2





(c) Test C-B-3

Figure 9 Movement trajectory and movement speed of wheelchair users in bidirectional evacuation experiments under self-propelled mode



(a) schematic diagram (b) experimental process

Figure 10 Influences of the dominant hand on walking path selection

To quantitatively compare the evacuation parameters of wheelchair users in the right-angle turn corridor under different width conditions, the ranges, means, and SD of the trajectory length, the time-averaged movement speed, and the time-averaged absolute angular speed are summarized in Table 5. Across all corridor width conditions, the trajectory length of the inner-path wheelchair users is shorter than that of the outer ones, with a difference of approximately 1.1 m. With increasing corridor width, the trajectory lengths of both inner- and outer-path wheelchair users decrease. Compared with the outer-path wheelchair users, the absolute angular velocity of the inner-path wheelchair users was larger due to their smaller turning radius. The absolute angular velocity of the inner-path wheelchair users decreased with increasing corridor width, whereas the corridor width had no significant effects on that of the outer users. This indicates that the corridor width exerts a greater influence on the evacuation process of the inner users during bidirectional evacuation experiments. As the corridor width increases, the turning radius of wheelchair users becomes larger, which makes the turning process easier and consequently leads to a decrease in the absolute angular velocity.

In terms of mean values, the movement speed of wheelchair users under different corridor width conditions ranges from 0.4 to 0.6 m/s, approximately. The movement speed of inner-path wheelchair users increases with increasing corridor width, which is consistent with the discussions on absolute angular velocity, whereas that of the outer-path wheelchair users shows no clear trend with increasing corridor width. The variation in the movement speed difference between the inner- and outer-paths wheelchair users is worth noting. Under the conditions with corridor widths of 1.8 m and 2.0 m, the time-averaged movement speed of the outer-path wheelchair users is higher than that of the inner ones, and this difference is more obvious under the 1.8 m-corridor condition. However, under the unrestricted width condition, the inner-path wheelchair users exhibit a slightly higher movement speed than the outer ones. From the analysis of the experimental videos, it was observed that under the width-restricted conditions, when the two opposing wheelchair users encountered each other and they were unable to pass at the same time, the inner-path wheelchair user usually slowed down and waited for the outer one to pass first. Taking an experiment in Scenario C-B-1 as an example, the crossing

process of the two opposing wheelchair users and their movement speeds during this process are shown in Figure 11. In this experiment, the two wheelchair users did not collide with each other. When they could not pass through the right-angle turn corridor simultaneously, the inner-path wheelchair user actively yielded and waited for the outer one to pass first. During this process, the movement speed of the inner-path wheelchair user dropped below 0.2 m/s. This is mainly because, under width-constrained conditions, the inner-path wheelchair users have less movement space compared to the outer ones. Consequently, when a conflict occurs, the inner users must wait and yield. In addition, based on brief oral interviews conducted after the experiments, some inner-path wheelchair users indicated that, since they had chosen the shorter route, they considered it reasonable for them to wait for the other to pass first, which might be a potential reason.

Table 5 Trajectory length, time-averaged movement speed, and time-averaged absolute angular speed in Test C-B

Evacuation parameters		1.8 m corridor		2.0 m corridor		Unrestricted corridor	
		inner	outer	inner	outer	inner	outer
Trajectory length, L (m)	Range	2.03~2.59	3.11~3.67	1.73~2.29	2.89~3.40	1.19~2.27	2.48~3.46
	Mean	2.311	3.384	1.993	3.131	1.811	2.929
	SD	0.146	0.153	0.166	0.165	0.296	0.297
Time-averaged movement speed, $\bar{v}$ (m/s)	Range	0.27~0.71	0.36~0.70	0.37~0.76	0.46~0.83	0.42~0.77	0.45~0.81
	Mean	0.400	0.533	0.499	0.609	0.592	0.577
	SD	0.118	0.125	0.143	0.116	0.097	0.104
Time-averaged absolute angular speed, $\overline{\lvert\omega\rvert}$ (rad/s)	Range	0.77~3.03	0.70~1.85	0.80~2.70	0.81~1.54	0.83~2.27	0.82~1.52
	Mean	1.648	1.064	1.482	1.116	1.293	1.134
	SD	0.565	0.354	0.509	0.232	0.473	0.211
Number of collisions		0		0		0	

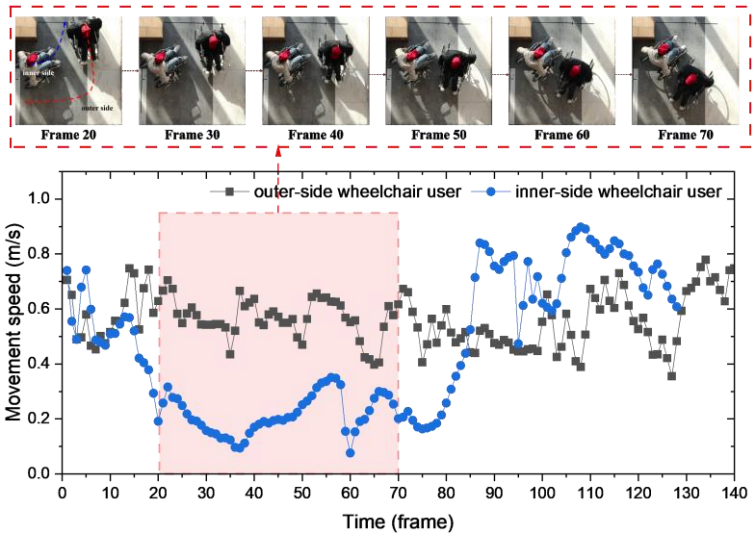
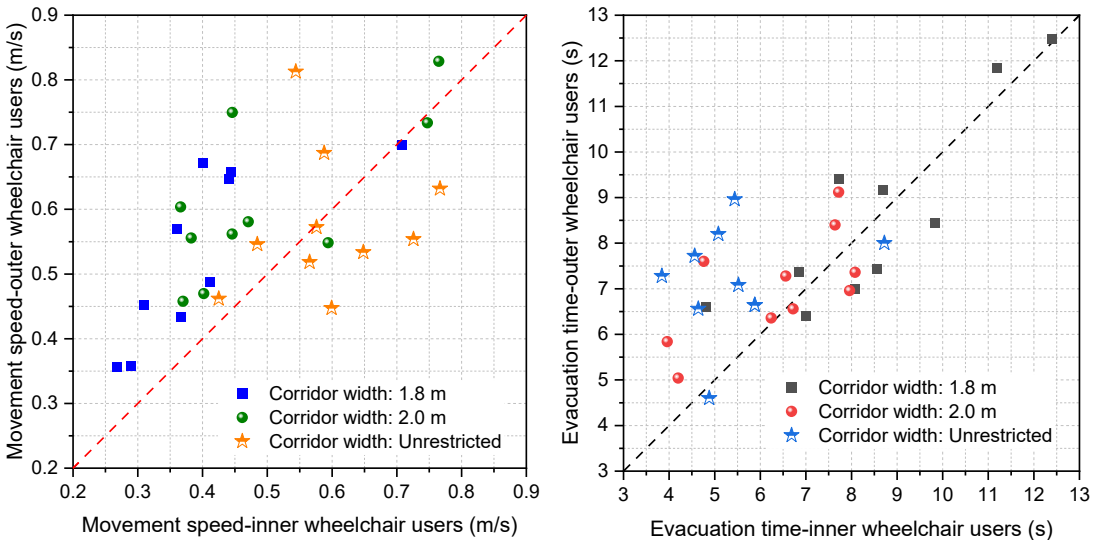


Figure 11 Crossing process and movement speeds of the inner- and outer-path wheelchair users (Scenario C-B-1, Test 2)

A comparison of the time-averaged movement speed and evacuation time between the wheelchair

users who chose the inner- and outer-paths under various corridor widths is shown in Figure 12. The evacuation times illustrated in Figure 12 were recorded by using an electronic stopwatch (from the moment the wheelchair users entered the experimental area until they left it completely). When the corridor width was 1.8 m, the outer-path wheelchair users exhibited higher movement speeds in 9 out of 10 experiments. When the corridor width was 2.0 m, this was observed in 8 out of 10 experiments. As discussed above, this is mainly due to the waiting and yielding behaviors of the inner-path wheelchair users when encountering opposite wheelchair users. Despite the shorter trajectory length of the inner-path wheelchair users, their reduced speed results in longer evacuation times through the right-angle turn corridor compared with the outer-path wheelchair users in nearly half of the experiments of Scenario C-B-1. In the condition with a corridor width of 2.0 m, there remained several experiments, in which the evacuation time for the inner-path wheelchair users was longer than that of the outer-path wheelchair users, and the proportion of these scenarios decreased compared to the 1.8 m width condition. In the unrestricted corridor scenario, the two wheelchair users on the opposite sides could pass the right-angle turn corridor simultaneously side by side. In this scenario, although there is no dominant side in movement speed between the inner- and outer-path wheelchair users, the evacuation time of the inner-path wheelchair users is still shorter in most experiments.



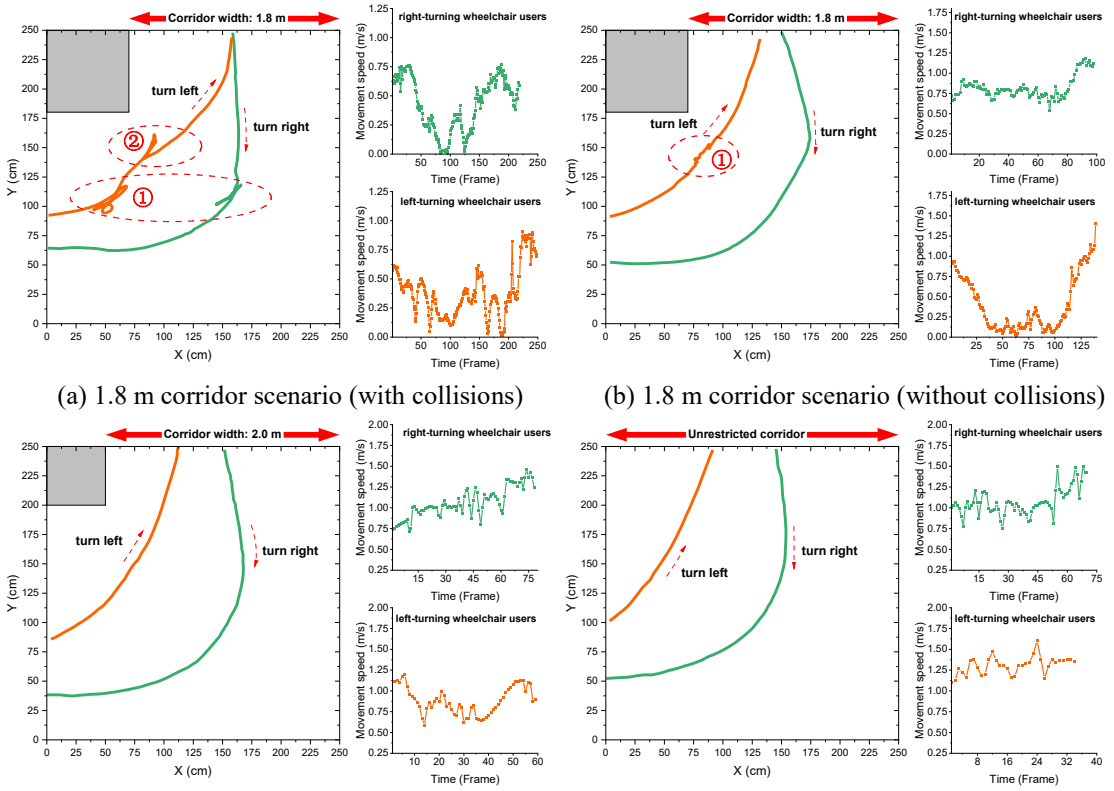
(a) movement speed (b) evacuation time

Figure 12 Comparisons of movement speeds and evacuation time between inner- and outer-path wheelchair users in Scenario C-B

4.2 Bidirectional evacuation of wheelchair users under pushing-assisted mode

Under the pushing-assisted mode, the movement trajectory and movement speed of typical wheelchair users in bidirectional evacuation experiments with 1.8 m, 2.0 m, and unrestricted corridors are shown in Figure 13. In the 1.8 m corridor width condition, a total of 7 collisions occurred in 10 experiments, among which 4 were collisions between opposing wheelchair users and 3 were collisions of a single wheelchair user with the corridor boundary. When a collision occurs between two opposite wheelchair users, they repeatedly move forward and backward to adjust their travel direction and avoid the conflict, as indicated by circle one in Figure 13 (a). As shown in circle two in Figure 13 (a), the inner wheelchair user subsequently collided with the inner corridor boundary after avoiding the conflict with the outer one. During both collisions, the movement speeds of the wheelchair users decreased

obviously. The experimental process corresponding to the trajectories and movement curves shown in Figure 13 (a) is illustrated in Figure 14. When the corridor width was 2.0 m, no collision occurred between the opposing wheelchair users, but only one inner wheelchair user collided with the inner corridor boundary. Under the experiments without collisions, as shown in Figure 13 (b) and (c), when the opposing wheelchair users were close and could not pass simultaneously, the inner user typically decelerated and yielded in conditions with restricted corridors, which was consistent with Scenario C-B. While the speed reduction in 2.0 m-corridor conditions is not as obvious as that in the 1.8 m-corridor conditions. In the unrestricted corridor scenarios, the wheelchair users on both sides had sufficient space to pass side by side; therefore, their movement speeds did not exhibit a significant decrease, as shown in Figure 13 (d).



(a) 1.8 m corridor scenario (with collisions)

(b) 1.8 m corridor scenario (without collisions)

(c) 2.0 m corridor scenario

(d) Unrestricted corridor scenario

Figure 13 Movement trajectory and movement speed of typical wheelchair users in Scenario D-B



Figure 14 Collisions and subsequent avoidance processes of typical wheelchair users in Scenario D-B-1

The ranges, means, and SD of the trajectory length, the time-averaged movement speed, and the time-averaged absolute angular speed of the wheelchair users in all experiments of Scenario D-B are summarized in Table 6. Compared with Table 5, the trajectory length of wheelchair users under the pushing-assisted condition is basically the same as that under the self-propelled condition. The advantage of the pushing-assisted mode in shortening trajectory length, which was observed in

unidirectional evacuation, was eliminated in bidirectional evacuation due to the influences of the opposing pedestrians. Under the 2.0 m-corridor and unrestricted width conditions, the mean absolute angular velocity in the pushing-assisted mode was lower than that in the self-propelled mode. However, under the 1.8 m-corridor condition, it was slightly higher—mainly due to the increase in collisions under the pushing-assisted mode. A comparison of the time-averaged movement speeds reveals that wheelchair users in the pushing-assisted condition exhibit higher movement speeds than those in the self-propelled condition for all scenarios. However, under the 1.8 m-corridor condition, the difference in time-averaged movement speed between the two modes was relatively small. Overall, the wheelchair users under the pushing-assisted mode show easier directional adjustment and higher movement speeds compared with those under the self-propelled mode, which is consistent with the unidirectional evacuation experiment. However, when the corridor is narrower (1.8 m in this study), the corridor width exerts a greater influence on the evacuation process of wheelchair users, resulting that the advantages of the pushing-assisted mode in terms of speed and directional control are diminished or even lost. When the corridor is wider (2.0 m and unrestricted in this study), the wheelchair users have larger space to complete the turning, and the propulsion mode of wheelchair users (self-propelled vs. pushing-assisted) becomes the more dominant factor affecting their evacuation process, and the advantages of the pushing-assisted mode in terms of speed and directional control become obvious.

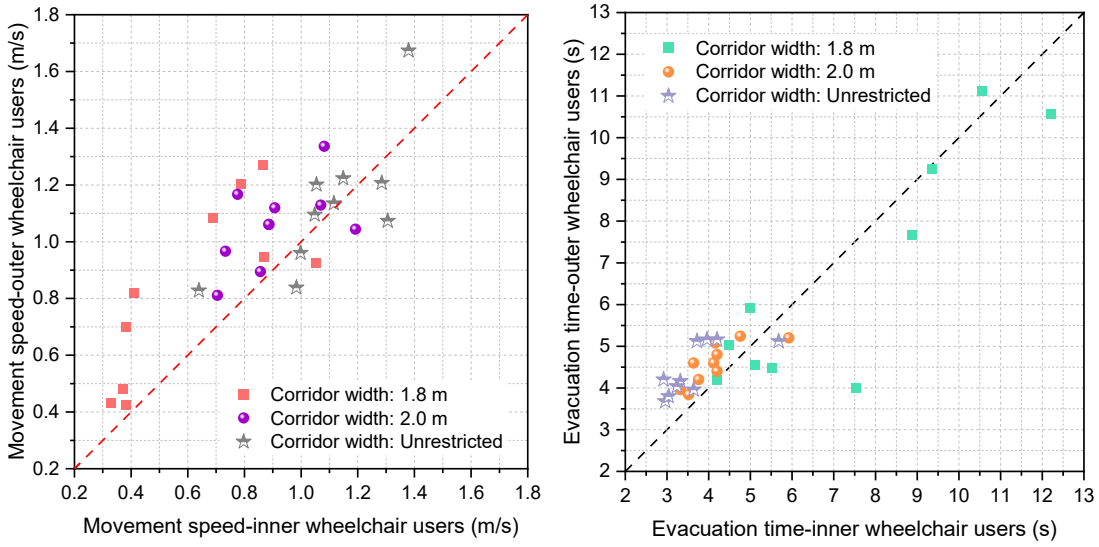
In the pushing-assisted evacuation scenario, collisions were observed in the experiments for both the 1.8 m and 2.0 m corridor widths. When the corridor width was 1.8 m, a total of seven collisions occurred across ten experiments. For the 2.0 m corridor width, one collision between an inner wheelchair user and the inner boundary was recorded. While, no collisions occurred between opposing wheelchair users in any of the the self-propelled evacuation experiments based on **错误!不能识别的开关参数。**. It shows that under the pushing-assisted condition, the opposing wheelchair users are more prone to collisions during their crossing process, as compared with the self-propelled condition. The difference in the number of collisions in self-propelled and pushing-assisted evacuation experiments may by primarily attributable to the difference in movement speeds. Based on **错误!不能识别的开关参数。** and **错误!不能识别的开关参数。**, compared with the self-propelled mode, the time-averaged movement speed of inner-path wheelchair users increased under the pushing-assisted mode by 0.213 m/s (53.25%) at 1.8 m, 0.411 m/s (82.36%) at 2.0 m, and 0.504 m/s (85.14%) in the unrestricted corridor condition; for outer-path wheelchair users, the speed increases at 1.8 m, 2.0 m, and unrestricted corridor conditions were 0.295 m/s (55.35%), 0.450 m/s (73.89%), and 0.546 m/s (94.63%), respectively. Refer to the studies of Ye et al. [47] and Gao et al. [48], the faster walking speeds of pedestrians would diminish the collision avoidance ability among opposing pedestrians, and increase the deceleration distance and avoidance space when encountering an obstacle. Although their studies focused on the normal pedestrians, the evacuation of wheelchair users should follow the similar characteristics. Therefore, the elevated movement speed of wheelchair users under the pushing-assisted mode makes them more difficult to coordinate a mutually acceptable avoidance trajectory when approaching each other, thereby increasing the probability of collisions. The larger obstacle-avoidance space required at higher speeds further explains why more collisions occurred in narrow-corridor conditions in the present experiments.

Table 6 Trajectory length, time-averaged movement speed, and time-averaged absolute angular speed in Scenario D-B

Evacuation parameters	1.8 m corridor	2.0 m corridor	Unrestricted corridor

		inner	outer	inner	outer	inner	outer
Trajectory length, L (m)	Range	1.83~3.76	3.08~3.97	1.73~2.27	2.86~3.27	1.65~2.28	2.81~3.43
	Mean	2.403	3.341	1.966	3.123	1.868	3.031
	SD	0.549	0.267	0.160	0.130	0.203	0.169
Time-averaged movement speed, $\bar{v}$ (m/s)	Range	0.33~1.05	0.42~1.27	0.70~1.19	0.81~1.34	0.64~1.38	0.83~1.67
	Mean	0.613	0.828	0.910	1.059	1.096	1.123
	SD	0.254	0.298	0.152	0.139	0.199	0.229
Time-averaged absolute angular speed, $\overline{\lvert\omega\rvert}$ (rad/s)	Range	0.59~3.84	0.63~2.00	0.34~1.57	0.44~1.01	0.55~1.02	0.70~1.13
	Mean	1.770	1.190	0.772	0.772	0.748	0.857
	SD	1.104	0.398	0.318	0.157	0.160	0.132
Number of collisions		7		1		0	

A comparison of the time-averaged movement speed and evacuation time between the wheelchair users that chose the inner-path and outer-path under the pushing-assisted mode is shown in Figure 15. In scenarios with the 1.8 m-wide corridor, inner wheelchair users have greater difficulty in reorienting after collisions with opposing wheelchair users and are also more susceptible to collisions with the inner boundary. Consequently, their movement speed is lower than that of the outer users in most trials. According to Table 6, in terms of mean values, the movement speed of the inner wheelchair users decreased by 26% compared with that of the outer wheelchair users. Therefore, as shown in Figure 13(b), although the inner wheelchair users followed a shorter trajectory, their lower movement speed resulted in longer travel times through the corridor in the majority of experiments. When the corridor width was 2.0 m, the movement speed of the outer wheelchair users remained higher than that of the inner wheelchair users in the majority of experiments. However, compared with the 1.8 m-corridor condition, this difference was reduced. Owing to the shorter movement trajectory, the inner wheelchair users generally had shorter evacuation times. In the unrestricted corridor conditions, the relative movement speed between the inner and outer users was roughly balanced with no clear trend in favor of either side, and their mean movement speeds were close. In this condition, the evacuation time of the outer wheelchair users is longer.



(a) movement speed (b) evacuation time

Figure 15 Comparisons of movement speeds between inner- and outer-path wheelchair users in

Scenario D-B

5. Conclusions

An experimental study on the evacuation behaviors of wheelchair users in right-angle turn corridors with varying widths was conducted in the present study. The main findings are summarized as follows:

(1) Corridor width is a key factor governing the evacuation performance of wheelchair users in L-shaped turns. Narrower corridors lead to increased trajectory lengths, reduced movement speeds, and elevated absolute angular velocities of the wheelchair users. The speed reduction during turning becomes more obvious as the corridor width decreases, and collisions with boundaries are more frequent.

(2) The pushing-assisted mode demonstrates clear advantages in emergency evacuation over the self-propelled mode in terms of directional control and movement efficiency in unidirectional evacuation experiments. Under the pushing-assisted mode, wheelchair users exhibit shorter trajectories, higher movement speeds (50.85% to 77.59% faster among different corridor width conditions), and lower absolute angular velocities. However, this advantage is less significant in narrow corridors where the spatial constraint dominates, and becomes more prominent when the corridor is wider ($\geqslant$2.0 m or unrestricted).

(3) In bidirectional evacuation experiments, the inner-path wheelchair users usually yield to the outer-path users when simultaneous passage is impossible, resulting in lower speeds and even longer evacuation times for the inner users despite their shorter trajectories. This yielding behavior is primarily attributed to the reduced maneuvering space on the inner side and a perceived fairness of the inner-path wheelchair users since they had chosen the shorter route. The effect diminishes as corridor width increases.

(4) No collisions occurred in any self-propelled bidirectional experiments across all widths, whereas in the pushing-assisted bidirectional condition, collisions were observed when the corridor widths were 1.8 m (7 collisions) and 2.0 m (1 collision). This phenomenon is mainly attributed to the higher movement speeds of wheelchair users under pushing-assisted mode. The elevated movement speed of wheelchair users under the pushing-assisted mode makes them more difficult to coordinate a mutually acceptable avoidance trajectory when approaching each other, thereby increasing the probability of collisions.

It is important to note that the participants in the experiments—university students who experienced a short-term practice in wheelchair operation—differ from the actual wheelchair users in terms of evacuation behaviors. First, the evacuation speed of wheelchair users is expected to increase as their proficiency in wheelchair use increases. Therefore, the actual wheelchair users are expected to have higher evacuation speeds than the university students who participated in the present experiments. The elderly or patient wheelchair users may have lower evacuation speeds under self-propelled evacuation mode compared with the non-disabled participants who have little experience in using the wheelchair. While such individuals are typically evacuated with the assistance of others in emergency situations. Second, the actual wheelchair operators generally have greater proficiency in directional control of the wheelchair compared with university students. Consequently, their evacuation trajectories are likely to be smoother, and the likelihood of the collisions with corridor boundaries or opposing wheelchair users is expected to be lower than that observed in the present study. To sum, under the same evacuation conditions, the actual wheelchair users would likely required shorter evacuation times than the non-disabled participants who operated wheelchairs. From this perspective, the conclusions reported in the present study are likely to be conservative estimates.

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