WALKING BEHAVIOR OF INDIVIDUALS WITH AND WITHOUT DISABILITIES AT RIGHT-ANGLE TURNING FACILITY

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***Abstract*:** To accommodate the needs of pedestrians, urban designers need to carefully consider pedestrian walking behavior in different walking environments. Detailed studies of the walking behavior of pedestrians have been conducted and used for pedestrian simulation models. A right-angle turning facility (RATF) is found in many built environments. Hence the study of pedestrians' walking behavior in RATFs is important to build pedestrian simulation models. Previous studies have failed to address the walking behavior of individuals with visual and mobility disabilities even though they comprise a significant portion of the population in the United States. The purpose of this paper is to provide a comparative analysis of the effect of indoor RATFs on individuals with and without disabilities. The objective of this study was to determine whether there is any difference in the length of turns in the RATFS of individuals with and without disabilities and see the effect of RATFS in the walking speed of the individual with disabilities (IWDs) and individuals without disabilities (IWODs). The results show that for RATFs, individuals with visual disabilities and those with mobility disabilities have different walking behavior from each other and from IWODs. Therefore, individuals with visual and mobility disabilities should be considered differently from individuals without disabilities in simulation models.

Keywords: right-angle corners, individuals with disabilities, walking behavior, pedestrian

Introduction

With increasing urbanization, it is necessary for urban designers to understand the behavior of pedestrians in order to accommodate their mobility needs. Pedestrian simulations are increasingly powerful tools for designing suitable pedestrian environments (Gorrini et al., 2016; Köster et al., 2011). To support reliable pedestrian simulations, many pedestrian studies have been conducted to understand walking behavior in various. (Daamen and Hoogendoorn, 2003; Helbing et al., 2005; Seyfried et al., 2009; Sharifi et al., 2015; Sharifi, 2016; Sharifi et al., 2016). However, there have been few empirical studies on the walking behavior of IWDs even though they comprise a large part of the population in the United States (Rubadari et al. 1997; Wright et al. 1999; Christensen et al., 2013). The percentage of people with disabilities has increased from 11.9% in 2010 to 12.6 % in 2014 (Kraus, 2015). Thus, IWDs are not well represented in pedestrian simulations or the subsequent design of pedestrian environments. Therefore, this study compared the walking behavior of individuals with and without disabilities in RATFs, to gain a better understanding of the walking behavior of IWDs.

Due to the lack of information about the walking behavior of IWDs, the ADA Standards for Accessible Design's technical specifications for designing public turning are based on the standard dimensions of a wheelchair (ADA Standards for Accessible Design, 2010). Powered wheelchairs require more space than manual wheelchair for making turns (Koontz et al., 2010). The Highway Capacity Manual (HCM), which is generally consulted for the design of walking facilities, does not consider IWDs in its guidelines for building walking facilities. The HCM has some provisions for the design of the pedestrian facilities but does not include IWDs in the provisions. ADAAG provides guidelines for the design of the pedestrian facilities taking IWDs into account but does not consider interactions among IWDs and IWODs. To design safe and comfortable walking facilities that support a diversity of pedestrians, it is necessary to understand the walking behavior of diverse individuals in such facilities. Presently, pedestrian simulation models fail to adequately include individuals with disabilities, primarily by reducing the speed of individuals with disabilities when they are included, which contributes to a lack of designed environments that accommodate the behavior of individuals with disabilities (Shi et al., 2015). Existing simulation model methods include cellular automata, social force models, activity choice models, velocity-based models, network models, continuum models and others as well (Duives et al., 2013).

Several controlled experiments have been conducted to study the walking behavior of pedestrians in different indoor facilities. Daamen and Hoogendoorn (2003) conducted an experiment to analyze pedestrian flow in the narrow bottleneck of a facility. The microscopic walking behavior of pedestrians was studied considering different variables like free speed, walking direction, density, and effect of bottlenecks. Helbing et al. (2005) also conducted experiments on various pedestrian aspects in the built environment, from which the self-organizing phenomenon found in the walking behavior of pedestrians was derived. Similarly, Seyfried et al. (2009) conducted a unidirectional pedestrian flow experiment in the narrow bottleneck of a facility under laboratory conditions. The collection of pedestrians’ walking behavior data led to the microscopic analysis of the walking behavior of the individuals at different facilities.

Turning facilities, found in many built walking facilities, have been examined previously; the results of which suggest that general population pedestrians when encountering turning facilities tend to move in a curved path determined by biomechanical factors and the geometric features of the path

(Hicheur and Berthoz, 2005). When pedestrians encounter a turning corner, they walk a circular path of around a 50cm radius around the corner (Lami et al., 2001). The change in the direction is not sudden but has to be planned before to reduce the acceleration of the body (Patla et al., 1991). Yanagisawa et al. (2009) investigated the decrease in pedestrians' walking speed while turning by relating it with turning friction (Ʈ), the decrease in walking speed when there is a change in direction. The effect of angled corridors on the flow of pedestrians has been statistically studied (Gorrini et al., 2013) by conducting a controlled experiment with 68 subjects which concluded that the flow rate is decreased with the introduction of angled corridors. Turning facilities are also found in merging angles. The study by Shiwakoti et al. (Shiwakoti et al., 2015), suggests the occurrence of weaving with reduced speed in these merging areas. Likewise, Dias et al. (2014) used numerical simulations that were then implemented to study pedestrians' walking behavior in angled corridors. Force based models (Helbing et al. 2000; Shiwakoti et al. 2011) have also been used to study pedestrians' walking characteristics in these walking environments. Shi et al.'s (2015) review on the study of turning movements found that not many studies have been conducted regarding the turning behavior shown by the pedestrians in angled situations. Although there were some studies of pedestrians' movement in turning facilities, not many studies have been found in the right angle turns, even though they are found in almost all building facilities. The experimental study by Dias et al. (2014) at right angle corridors with a total of 16 participants, under three scenarios (typical speed walking, high speed walking and slow running), concluded that the pedestrians tend to form a horizontal curve with reduced speed at the vicinity of angled corridors. Understandably, discrete pedestrian simulations model lower speeds during right-angle turns described by pedestrians yielding their movement (Bandini et al., 2014).

None of the studies above examined the walking behavior of the individuals with disabilities. There has been some study concerning the walking behavior of individuals with disabilities, but these tend to focus on evacuation routes and conditions (Rubadari et al. 1997; Wright et al. 1999; Christensen et al., 2013). An experimental study on the evacuation behavior of individuals with visual impairments revealed that there was mixed behavior among them (Sorensen et al., 2013). The effects of white canes, guide dogs, handrails and walls on the navigation of the exit were studied. Not many studies have been found on the typical walking behavior of the IWDs in the built environment. One study has shown that the space required by the powered mobility scooters for the IWDs to make turn is more than that necessary to avoid a counter or work surface from the side (Dutta et al., 2011). Comparative study of the standards for those relying on wheeled mobility in different walking environments suggests that these standards should be revised for easier access of the wheelchairs (Steinfield et al., 2010). Another study to differentiate walking speed among homogeneous and heterogeneous groups showed that the mean walking speed of heterogeneous groups is lower than the homogeneous group in different walking facilities and other small differences were found in their walking behavior (Sharifi et al., 2015; Sharifi, 2016; Sharifi et al., 2016).

It seems clear that the study of individuals with disabilities' walking behavior has found very little attention in the literature. Further, no studies have been found on the walking behavior of IWDs in RATFs. Therefore, the purpose of this study was to compare the walking behavior of individuals with and without disabilities in RATFs. The first objective of this study was to determine whether there is any difference in the length of the turns of individuals with and without disabilities when they encounter RATFs. The second objective of this study was to examine the effect of turns in RATFs on the walking speeds of individuals with and without disabilities. The results from this study will provide information about the differences in walking behavior of individuals with and without disabilities, which could be used to improve pedestrian simulation models.

Methodology

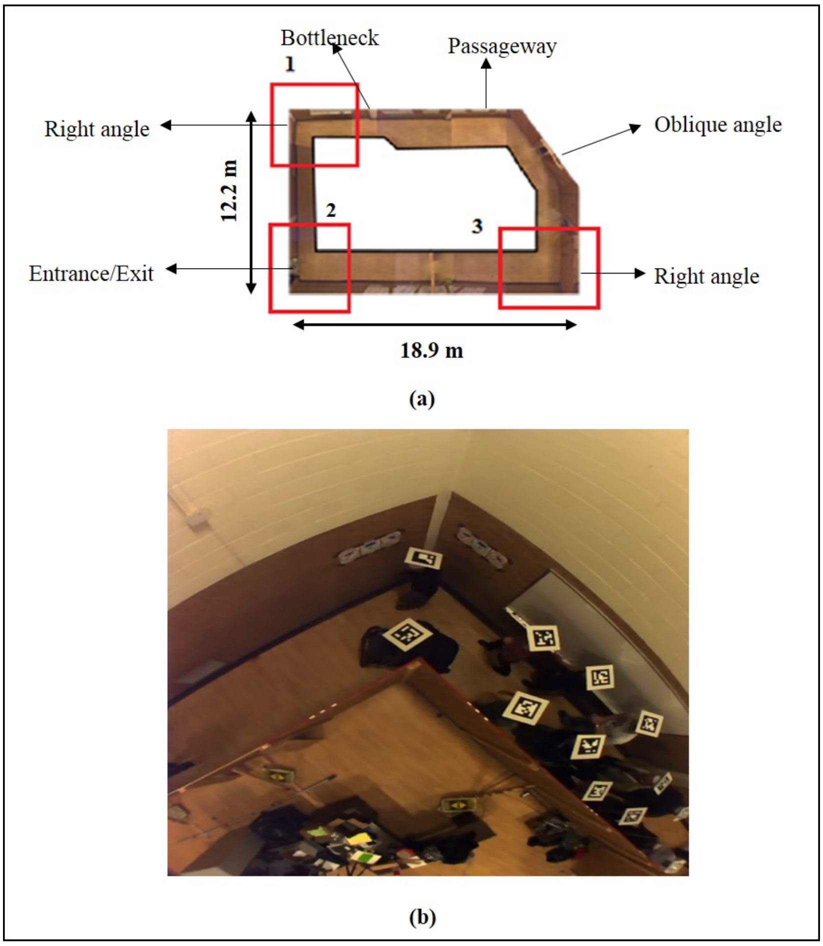
Experiment Design

With a focus on examining the behavior of different types of pedestrians, including IWDs, in different indoor walking environments, a controlled indoor experiment was carried out at Utah State University (USU). Different walking facilities (passageways, RATFs, oblique angle corridors, and bottlenecks) were considered. As shown in Figure 1, the experiments were conducted in a temporary circuit using self-standing wall panels constructed according to Americans with Disabilities Act Accessibility Guidelines (ADAAG) for door and passageway widths, etc. IWDs were recruited in collaboration with the Center for Persons with Disabilities (CPD) at USU. Participants represented individuals having physical disabilities (individuals with motorized wheelchairs, individuals with non-motorized wheelchairs, individuals walking with the use of crutches), visual disabilities and other disabilities. Unique markers were worn by the participants using mortar boards or graduation caps, which were read by cameras above the experimental area to allow the tracking of their movement. The walking trajectory of the individuals was collected using the automated video identification and tracking technology (Sharifi et al. 2015). Readers are referred to (Sharifi et al. 2015) for the detailed information about the experimental setup.

This study uses the data collected during the unidirectional portion of the experiment to understand the difference in walking pattern of individuals with and without disabilities in RATFs. For the unidirectional portion of the circuit experiment, a total of 170 people participated, which included 146 people without disabilities and 24 with different types of disabilities. People with disabilities consisted of 9 with visual impairment (all of which required the use of a white cane, 5 with motorized wheelchair, 6 with non-motorized wheelchair and 4 individuals walking with forearm crutches. Walking experiments were divided into 10-minute multiple lap experiment sessions, during which participants were asked to move at their maximum comfortable speed, resulting in about 2 hours of data collection. To acquire the data across congestion levels, the entry and exit of the participants were controlled during the experiment. The participants (both individuals with and without disabilities) were entered from the entry door at controlled times, walked in one direction around the circuit, and after the participant completed about 2 to 4 laps, they were taken out from the same exit door.

Figure 1 shows the layout of the experiment area. There were three different right-angle turning facilities in the layout of the experiment. The analysis was done for the RATF 1 as shown in Figure 1. RATF number 2 (see Figure 1) was omitted because the facility also had the door facility where the movement of the pedestrians would be affected by the entry and exit of the other individuals. Similarly, RATF number 3 in Figure 1 was avoided because of its closeness to the oblique angle facility.

Figure 1. (a): Experiment circuit indicating the various facilities: bottleneck, passageway, oblique angle, entrance/exit, and RATFs; (b): RATF with pedestrians walking according to one scenario. Source: authors.



Methods

The unidirectional flow trajectory data for every individual was examined at 0.2 second intervals, and their individual trajectory was analyzed, at the RATF between the individuals with and without disabilities. Also, the walking speed of the individuals at the right-angle periphery was calculated to analyze the walking speed pattern in the RATF per instantaneous speed for 0.2 second intervals.

Turn Initiation and Completion

When observing the trajectory of the individuals in the RATFS, individuals do not change their direction abruptly, but they change their direction gradually to the desired direction. The tangent length formed by the intersection of the two tangents were named as turn initiation length and turn completion length as shown in Figure 2.

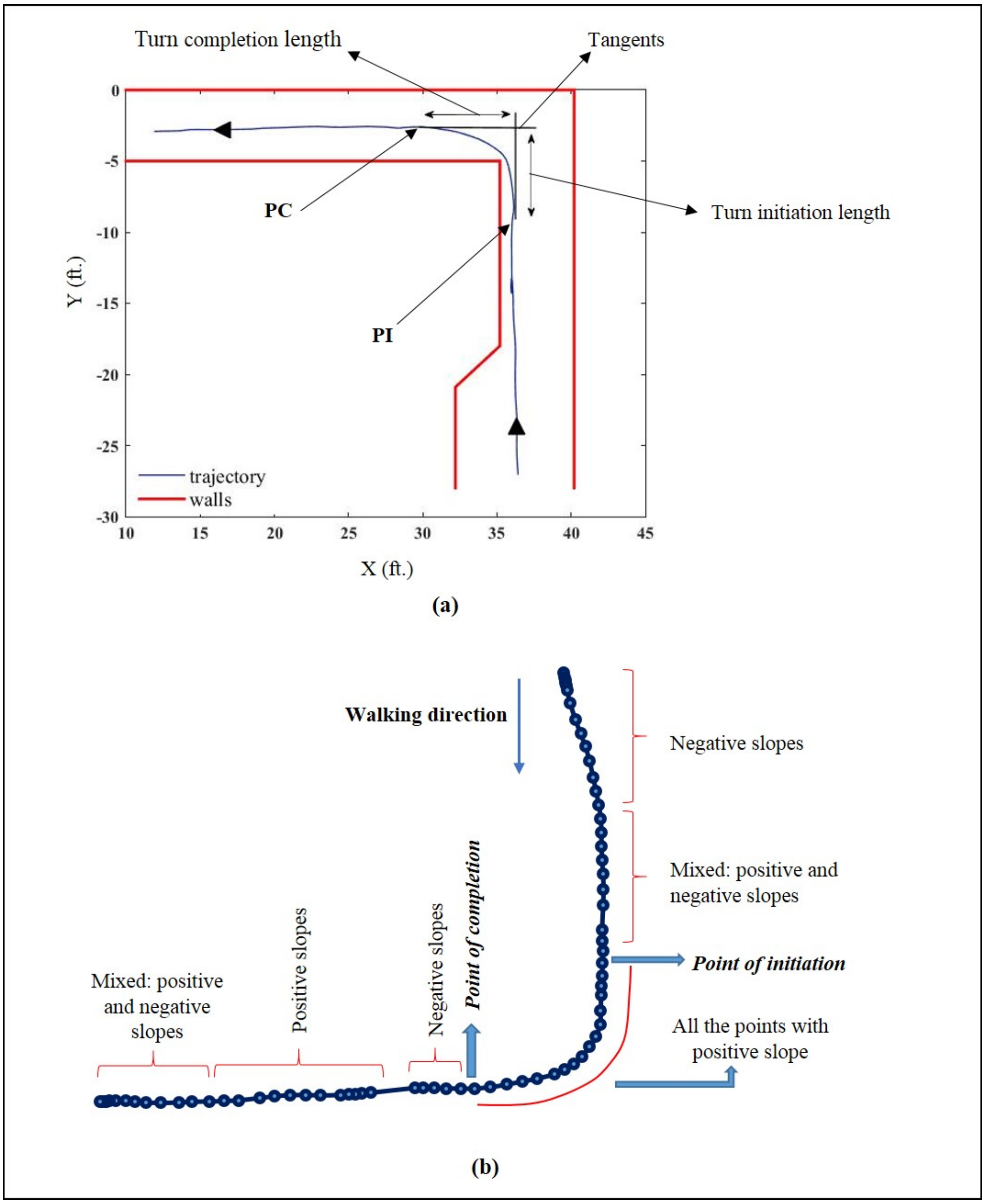
To find the point of initiation and point of completion, orientation of the individuals was examined. Using the slope equation between two adjacent points (x_1, y_1) and (x_2, y_2) in the trajectory of the individual, the trajectory slope of the individual in different points were calculated.

$slope = \frac{y_2 - y_1}{x_2 - x_1}$ where,

(x_1, y_1) and (x_2, y_2) are the coordinates of consecutive points in the trajectory of individuals.

After calculating the slope of the individual's trajectory, the direction of the individuals in the vicinity of RATFS was examined, and the point where the individuals start to change direction was named as turn initiation point. If the orientation of the individuals at the RATF was examined, they have same the sign of slope (positive) throughout the curve. The point they change the direction after making the curve is the point where the curve ends. This point where they change the direction was named as turn completion point.

Figure 2. (a): Trajectory of an individual traveling through a RATF; (b): Diagram of how turn initiation and completion points were determined from an individual's trajectory changes. Source: authors.



As shown in Figure 2, the trajectory of the individual contains both negative and positive slopes. The portion of the trajectory containing consecutive points with positive slope is the turning curve. As shown in Figure 2, not only the does the curved portion in the vicinity of RATF consists of points with positive slope, but other portions also do have consecutive points with positive slope. To automate the process, the curve portion was differentiated from other portions with consecutive positive slopes by fitting a circle at very portion of curve containing consecutive points with positive slope. The radius of circle for doing this differentiation was taken as 8 ft., which was determined by sensitivity analysis for some trajectories. Hence, the curve at the RATF was distinguished and intersecting tangents drawn to the curve at the points of turn initiation and completion gives us turn initiation and completion lengths.

Deceleration Pattern in Right-angle turning facility

The walking speed of all the individuals at the RATFS was analyzed to see whether there is any difference between IWDs and IWODs. The walking speed of all the individuals was calculated for a 0.2 second interval and the walking speed diagram was constructed.

Analysis and Results

Turn Initiation and Completion

For the following analysis individuals with visual disabilities were excluded as their turning curve pattern was distinct from that of other individuals with disabilities. A total of 161 individuals, 146 without disabilities and 15 with different types of mobility disabilities, were included in this analysis.

Table 1 provides information about the turn initiation and completion length for 2 groups: without disabilities and with disabilities. IWODs consisted of 146 different trajectory samples, whereas individuals with mobility disabilities consisted of 35 different trajectory samples. Individuals with mobility disabilities have been sub-divided into different categories according to the different mobility disability types in Table 2. As the mean length for the turn initiation and turn completion for different types of mobility disabilities were not significantly different, they were considered in a single group for the evaluation. The mean length of turn initiation and turn completion was calculated along with the standard error for each sample.

Table 1. Average values of turn initiation and completion lengths at right-angle turning facility.

Ids	Turn initiation (meters)	Turn completion (meters)
Without Disabilities (146 Samples)	1.44 (+-0.27)	1.57 (+-0.31)
With Disabilities (35 Samples)	2.13 (+-0.2)	2.14 (+-0.19)

Table 2 provides comparative information about the turn initiation and turn completion length for individuals with different types of disabilities.

Table 2. Average values of turn lengths for individuals with mobility disabilities.

Ids	Turn initiation (meters)	Turn completion (meters)
Motorized (11 Trajectories)	2.11 (+-0.19)	2.15 (+-0.22)
Non-Motorized (14 Trajectories)	2.2 (+-0.16)	2.14 (+-0.16)
Crutch (10 Trajectories)	2.06 (+-0.2)	2.13 (+-0.2)

Hypothesis testing was done to analyse the difference in turn initiation and turn completion lengths for different types of individuals.

Hypothesis 1: There is no difference in turn initiation length (μ) for individuals with mobility disabilities and individuals without disabilities.

$$Ho: \mu_{\text{individuals with mobility disabilities}} = \mu_{\text{individuals without disabilities}}$$

$$Ha: \mu_{\text{individuals with mobility disabilities}} \neq \mu_{\text{individuals without disabilities}}$$

This hypothesis testing was done to evaluate whether there is a significant difference in terms of the mean turn initiation length for individuals with mobility disabilities and without disabilities at the right-angle turning facility. The mean turn initiation length for individuals with mobility disabilities and without disabilities was tested at a 95% confidence interval. The results from the Z-test rejected the null hypothesis indicating that there is a significant difference in turn initiation length for the individuals with and without disabilities.

Hypothesis 2: There is no difference in turn completion length (μ) for individuals with mobility disabilities and individuals without disabilities.

$$H_o: \mu_{\text{individuals with mobility disabilities}} = \mu_{\text{individuals without disabilities}}$$

$$H_\alpha: \mu_{\text{individuals with mobility disabilities}} \neq \mu_{\text{individuals without disabilities}}$$

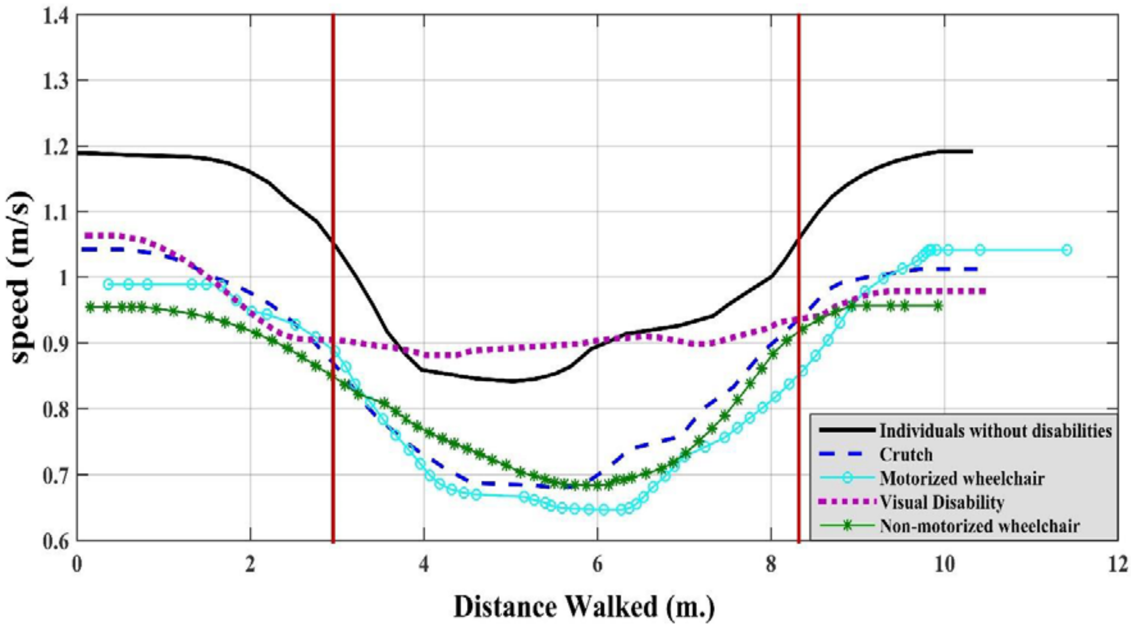
The mean turn initiation length for individuals with mobility disabilities and without disabilities was tested at a 95% confidence interval. The results from the Z-test rejected the null hypothesis indicating that there is also a significant difference in turn completion length between individuals with and without disabilities.

Deceleration Pattern in Right-angle turning facility

As the pedestrians had circular motion at the periphery of the RATFS, it was necessary to see whether this circular motion had any effect on the walking speed of the individuals. If the walking speed of the individuals is analyzed properly, it shows that individuals tend to reduce their walking speed before they encounter the turn and regain their normal walking speed after they complete the turn. This region where they reduce their speed can be termed as the “turning region.”

The walking speed of different IDs was analyzed on different laps for a single individual to study whether there is any difference in the deceleration pattern. For the IWDs other than individuals with visual disabilities, the deceleration pattern was found to be similar (speed decreases as they approach the RATF and increases after they complete their turn) as shown in Figure 3. The speed reduction pattern is found in all the individuals (both with and without disabilities) other than individuals with visual disabilities. For individuals with visual disabilities, walking speed pattern was found to be different than all other types of individuals. Hence, in the next section, an analysis of individuals with visual disabilities only will be performed, and the reasons will be examined.

Figure 3. Walking speed pattern of different types of individuals near RATFs, showing the U profile with the exception of individuals with visual disabilities whose profile is generally flat. Source: authors.



Analysis on Individuals with Visual Disabilities

After analyzing both turning behavior and speed pattern for all individuals, it was found that individuals with visual disabilities do not follow the same pattern as other individuals do. They do not have a distinct turning curve and turn initiation and completion points at the RATF.

Figure 4. Individual with visual disability at right-angle turning facility; (a): walking near the wall; (b): navigating the wall; (c): walking along the wall after making the turn. Source: authors.

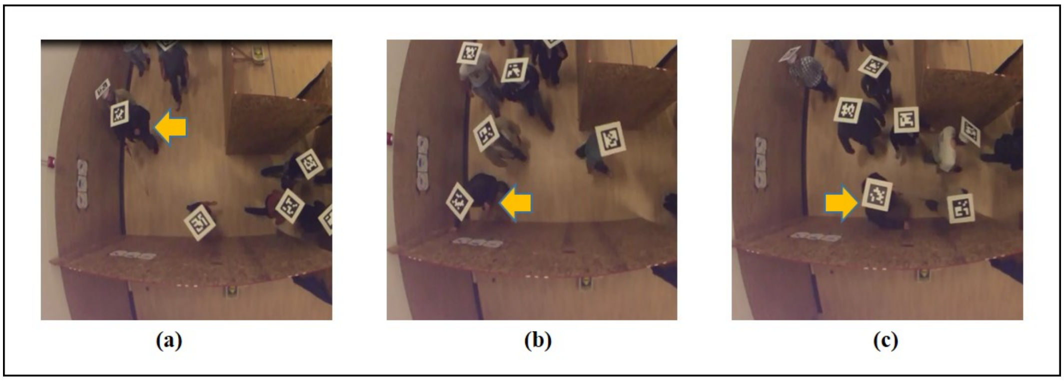
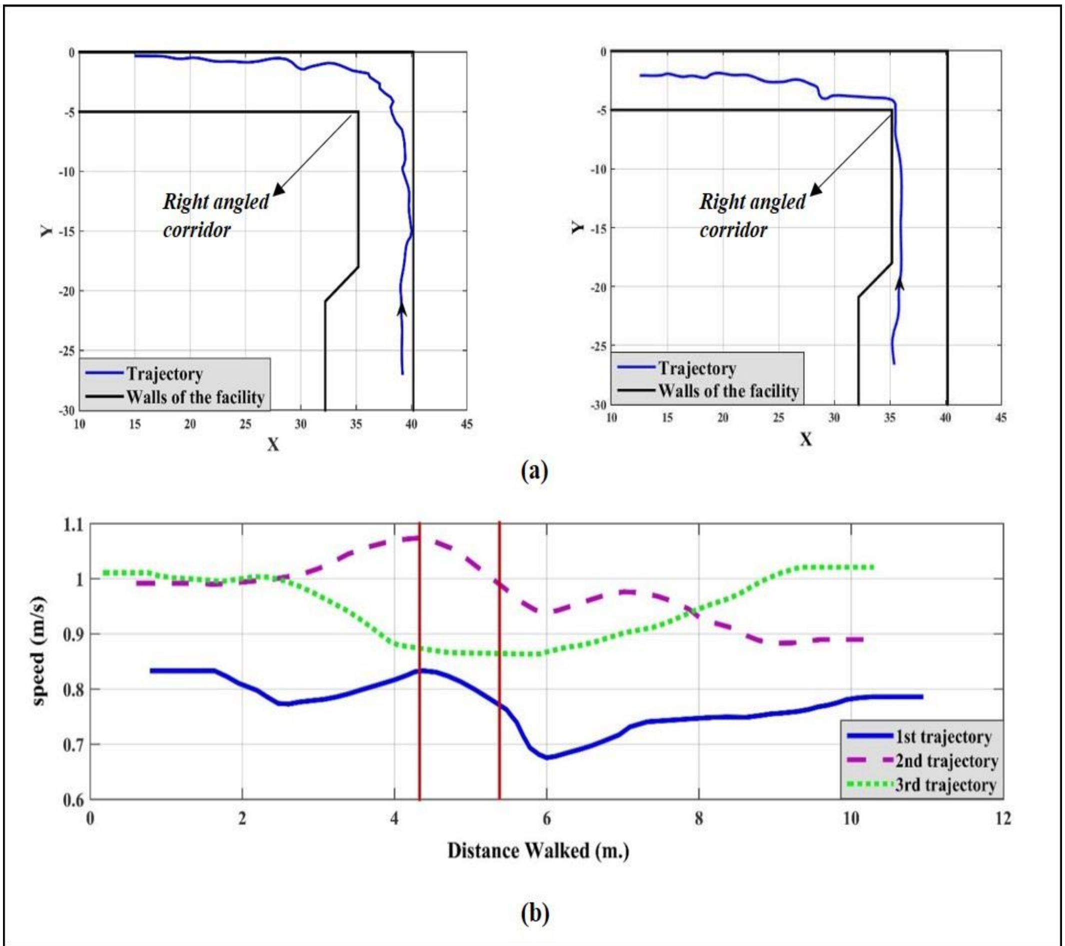


Figure 5. Example walking behavior of individuals with visual disabilities; (a): trajectory of two different individuals with visual disabilities showing the abrupt change in trajectory; (b): walking speed patterns of three individuals with visual disabilities for the entire circuit indicating the shared drop in speed for the RATF. Source: authors.



The trajectory pattern of individuals with visual disabilities does not have distinct turning curve (Figure 4). But some of the individuals who were walking with the assistance of the IWODs show the turning curve, but it is not as distinct as the other individuals. This pattern can be seen in Figure 4. This walking behavior leads to two results. The first result is that individuals with visual disabilities do not a have distinct turning curve around RATFs. As individuals with visual disabilities move alongside the wall, they do not tend to make a curve before and after encountering the turn as was found for all other types of individuals. The second result was that they do not have the deceleration pattern near RATFS as found in all other types of individuals as shown in Figure 4. This is because they walk only with the reference of the wall and when they encounter the turn, they reduce walking speed afterwards, as shown in Figure 5.

Conclusion

Individuals encounter different walking facilities daily in buildings, public places and, mass gatherings. Designing facilities to alleviate the difficulties faced by individuals while navigating the walking facility is of prime concern for a designer. This study was focused on examining the effect of RATFs on the walking behavior of individuals with and without disabilities. Primary study of the trajectories of the individuals showed that they tend to follow a curve when they encounter RATFs. But the detailed study showed that individuals with mobility disabilities have turning lengths much larger than IWODs at the RATFS, while individuals with visual disabilities do not have such a pattern as others do at the RATFS. Further, we conclude that the walking speed pattern of different individuals decreases towards the vicinity of the RATF.

However, individuals with visual disabilities show unique characteristics from other individuals. They do not have a distinct trajectory curve at the RATFS as other individuals do. They tend to walk alongside the walls, as shown in Figure 5, and cross the RATF without making a turning curve. Also, they do not reduce speed in the periphery of the RATF as other individuals do, but only reduce speed after they navigate the RATF and walk along with the wall (Figure 5).

Existing simulation models reduce the walking speed of all individuals within a turning region defined by the yielding of their movement at these turns (Bandini et al., 2014). This study shows that individuals with visual disabilities do not have the speed reduction tendency at the RATFS as other types of individuals, which provides insight for improved simulation models. Present studies suggest that in pedestrian simulation models all individuals are considered same. As individuals with visual disabilities showed different characteristics than all other types of individuals, they should not be considered like other individuals in the simulation models. There are very few policies regarding the walking behavior of the IWDs in existing codes (HCM and ADAAG), which perpetuates the design of walking facilities not addressing IWDs' pedestrian needs. As the walking behavior differs among individuals with different disabilities, they all should be considered different in simulation models and policy making.

In future studies, the walking pattern of heterogeneous populations can be examined for bidirectional flows. The change in their direction based on the opposite flow could be useful to study their strategies during multidirectional flows. There have not been many policies regarding the walking behavior of the IWDs in the existing codes (HCM and ADAAG), which makes design of the walking facilities not being too favorable for the IWDs. Changes in the walking speed of heterogeneous populations per changes in density and direction should be analyzed, which will give better insight into how IWDs influence the walking speed of heterogeneous group when they encounter other walking towards them.

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