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A large-scale controlled experiment on pedestrian walking behavior involving individuals with disabilities

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Abstract

It is imperative to design walking facility infrastructures to accommodate the needs of all pedestrian, including individuals with disabilities. Unfortunately, individuals with disabilities are often overlooked due to the lack of available data. The purpose of this study was to measure the individual pedestrian walking behaviors of individuals with disabilities through controlled video tracking experiments of heterogeneous crowds in various walking facilities; including passageways, right and oblique corners, doorways, bottlenecks, and stairs. The goal of this paper is to provide an overview of conducting experimental research on pedestrian walking behavior involving individuals with and without disabilities, including automated video tracking methods, data collection, logistical issues, processing methods, and lessons learned from conducting a large-scale study. The findings support future large-scale experiments related to the pedestrian walking behavior of individuals with disabilities. The results can be used to calibrate and validate pedestrian traffic flow models capturing the behaviors and interactions of crowds which include different types of individuals with disabilities.

Keywords individuals with disabilities; pedestrian; behavior; crowds; research methods

1. Introduction

Walking facilities are important infrastructures which must be designed to accommodate the behavior of pedestrians to be effective. Heterogeneity in pedestrian composition is one important factor generally overlooked in walking facility design guidelines. Particularly, individuals with disabilities are often overlooked due to a lack of available data on their pedestrian behaviors. Yet individuals with disabilities represent a significant portion of the population, accounting for 12.6% of the working age population (i.e., about 30.2 million) and 16.7% of the total population (i.e., about 51.5 million) of the United States (U.S. Census Bureau, 2010).

In the United States, the International Building Code (IBC) (ICC, 2012) comprises the relevant health, safety, and welfare codes for the design and construction of walking facilities. However, the guidelines overlook heterogeneity in pedestrian composition. To account for the needs of individuals with disabilities, the Americans with Disabilities Act Accessibility Guidelines guide the design and construction of accessible walking facilities for individuals with disabilities. These codes grew out of civil rights policy, the ADA, and are not necessarily evidence-based practices, but were developed through a public consensus process. Whether these regulatory standards, particularly those for pedestrian environments, effectively protect the health, safety, and welfare of individuals with disabilities is not well understood and little empirical research has been conducted to evaluate the standards for individuals with disabilities' needs.

Shi et al. (2015) completed a comprehensive review of the literature and found a great deal of research has been done to collect and observe pedestrian walking behavior. For example, Sisiopiku and Akin (2003) studied pedestrian behaviors and perceptions toward different pedestrian facilities such as signalized and unsignalized intersection crosswalks, unsignalized midblock crosswalks, physical barriers and crosswalk furniture. Some studies involved walking experiments to examine pedestrian behaviors in specific built environments and controlled conditions such as crowd environments. Daamen and Hoogendoorn (2003) conducted walking experiments in the Netherlands to derive walking behaviors in passageways and bottlenecks under different pedestrian flow scenarios such as un-directional, bi-directional, and cross pedestrian flows. Eighty individuals participated in ten experiments performed to observe pedestrian walking behavior in standard, station, and shopping conditions. The experimental process was recorded using a wide lens digital camera and walking trajectories were extracted and analysed to present microscopic (i.e., walking speed) and macroscopic (i.e., pedestrian flow) characteristics of the pedestrian stream in the various experimental scenarios.

Another series of large-scale walking experiments were conducted in Germany to observe pedestrian behaviors in corridors (Zhang, 2012; Zhang et al., 2012), bottlenecks (Seyfried et al., 2008; Seyfried et al., 2009; Kretz et al., 2006). Most of these studies explored macroscopic fundamental diagrams to study the impacts of different environments on the relationships of pedestrian speed, flow, and densities. Turning movements of pedestrians have been studied in complex geometrics such angled corridors (Dias et al., 2013; Dias et al., 2014, Gorrini et al., 2013; Aghabayk et al., 2015). For example, Dias et al. (2013) conducted a series of walking experiments to understand how different angled corridors impacted walking speed of individuals. They found that angles of more than 90 degree can significantly decrease the walking speed. While these empirical studies provide valuable knowledge on pedestrian needs, none of these studies addressed vulnerable pedestrians such as individuals with disabilities. The lack of research on the walking behavior of individuals with disabilities is in part due to the difficulty of data collection.

Notwithstanding, there are a limited number of studies on the walking behaviors of individuals with disabilities. For instance, Pecchini and Giuliani (2015) studied street crossing behaviors of individuals with disabilities. People with different types of disabilities were surveyed and design recommendations were suggested to better include the needs of individuals with disabilities. Few studies conducted controlled experiments to study on behaviors of individuals with disabilities. Boyce et al. (1999a) measured egress speed of 155 individuals involving unassisted ambulant, unassisted wheelchair users, assisted ambulant and assisted wheelchair users on level surfaces, ramps, corners, and stairs. They also conducted another study to measure the ability of 113 individuals with disabilities to negotiate doors (Boyce et al., 1999b). Kuligowski et al. (2013) conducted an experiment in a six-story building and studied the stair evacuation speed of older adults and people with mobility impairments. Wright et al. (1999) evaluated walking speed of 30 individuals with visual impairments through an egress route. Miyazaki et al. (2003) carried out a series of experiments using 30 participants and one participant with a wheelchair to describe the behavior of individuals encountering an individual using a wheelchair in a corridor with variable widths. Daamen and Hoogendoorn (2011) conducted an experiment to investigate the capacity of doorways with consideration of the elderly and people with disabilities in the Netherlands. In their experiments 75 children, 90 adults, 50 elderly individuals, 3 individuals using wheelchairs, and 3 individuals with visual impairments took part. The researchers tried to simulate different stress levels and collected behavior data using digital video and an infrared video cameras. Review of past studies demonstrates that most studies focused on the egress behavior of individuals with disabilities and few articles addressed the ability of individuals with disabilities to negotiate built environments in crowded situations. Therefore, large-scale empirical research is needed to examine to what extent the behavior of individuals with disabilities is affected by U.S. built environment regulatory standards.

To address this lack, in 2012 a series of large-scale controlled pedestrian behavior experiments which included individuals with disabilities were carried out at Utah State University (USU). The purpose of the study was to measure the stated and revealed pedestrian walking behaviors of individuals with disabilities in different walking facilities, including a level passageway, right angle, oblique angle, doorway, bottleneck, and stairway. This paper provides an overview of experimental research on individuals with disabilities' pedestrian walking behaviors, including automated video tracking methods, data collection, logistical issues, processing methods, and lessons learned from conducting a large-scale study. Moreover, this paper compares walking behavior differences between individuals with and without disabilities. Specifically, statistical analysis are presented to investigate the walking speed and spacing behaviors of different individual types. The findings support future large-scale experiments related to pedestrians with disabilities' walking behavior and advance our empirical understanding of the pedestrian behaviors of individuals with disabilities.

2. Experimental Methods

2.1. Participants recruitment

Study participants were a mixture of people without disabilities and people with mobility-related physical, sensory, or other types of disabilities, including hearing and intellectual impairments. The criteria for a mobility-related disability were based on the definition from the U.S. Census Bureau's American Community Survey (ACS) (U.S. Census Bureau, 2010) as: (Sensory Disability) blindness, deafness, or a severe vision or hearing impairment; (Physical Disability) a condition which substantially limits basic activities such as walking, climbing stairs, etc.; or (Go-Outside-Home Disability) a condition which creates difficulty in going outside the home to shop or visit a doctor's office. Participants with disabilities were recruited in collaboration with the Center for Persons with Disabilities (CPD) at USU. Study participants without a mobility related disability were selected from USU students. Participants were partially compensated for their time with a $50 stipend for each day of experiments.

In total, 311 individuals between 17 and 80 years old participated. Specifically, we recruited 231 participants (189 without disabilities and 42 with disabilities) for the circuit experiments and 80 participants (60 without disabilities and 20 with disabilities) for the stair experiments. For the circuit experiments about 26% of the participants with disabilities had a visual impairment, 38% had a physical impairment, and 36% had other types of disabilities. For the stair experiments, 35% of the participants with disabilities had a visual impairment, 25% had a physical impairment and 40% had other disability types. Some participants had more than one disability. Figure 1 shows the distribution of disabled participants in both the circuit and stair experiments. For detailed information about participant recruitment process, readers are referred to Sharifi (2016), Sharifi et al. (2015a), Sharifi et al. (2015b), Sharifi et al. (2016) and Stuart et al. (2015).

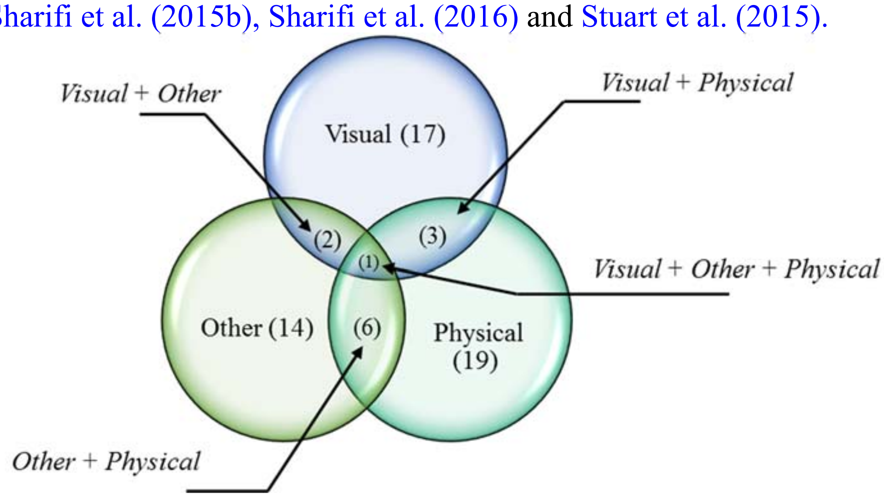
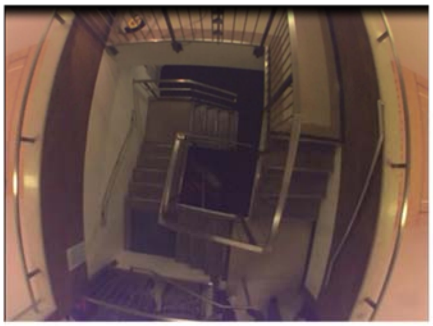


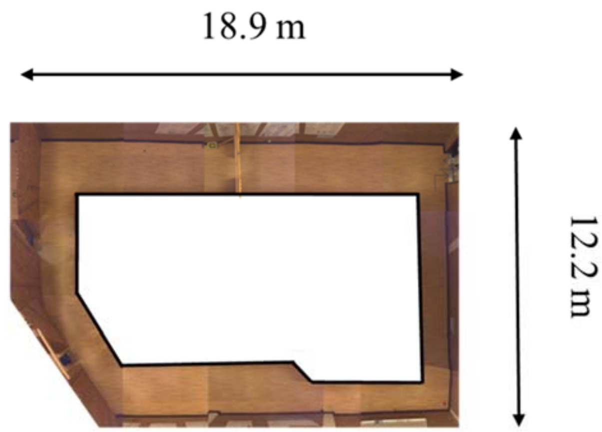
Fig. 1. Distribution of disabled participants.

2.2. Setting

For the crowd experiments, the Motion Analysis Lab of USU's department of Health, Physical Education and Recreation (HPER) was selected. The 280 square meter laboratory with 8-meter high ceilings was conducive to video tracking technology and camera suspension. A circuit was temporarily constructed within the Motion Analysis Lab to allow participants to pass through various walking facilities in an efficient loop. Eight foot tall panels formed the walking facilities designed to comply with Americans with Disabilities Act Accessibility guidelines (ADAAG, 2002) and the International Building Code (ICC, 2012). For the stairwell experiments, two standard stairwells in the HPER were chosen. Figure 2 presents the layout of the study areas.



(a)



(b)

Fig. 2. (a) staircase; (b) circuit.

2.3. Experimental measures

Before running the experiment, independent variables, which can be controlled during the experiment, and the dependent variables to be observed should be selected. Many factors affect pedestrian behavior, including an individual's characteristics (age, gender, health, disabilities, etc.), characteristics of the environment (type, dimensions, attractiveness, etc.), and ambient conditions (temperature, visibility, etc.). To make the experiment manageable, only significant independent variables were included for experiments and they were divided into two categories: experimental variables related to the built environment and context variables related to the characteristics of the individuals. Also, dependent variables were classified into two groups: microscopic and macroscopic variables. Primary microscopic dependent variables were identified from previous studies (Daamen and Hoogendoorn, 2003; Helbing et al., 2005) including, (1) the speed of the participants in meters per second, (2) the latitudinal and longitudinal distances maintained between the participants, other participants, and components of the environment, and (3) the walking trajectory. Macroscopic dependent variables like traffic flow diagrams were also included as a basic measure for evaluating the walking facilities. Table 1 presents experimental variables.

Table 1. Experimental variables

Independent variables	Experimental variables	Walkways • Level passageway • Right angle • Oblique angle • Bottleneck • Doorway Stairway Direction • Uni/bidirectional • Flow compositions • Density level
	Context variables	Physical disabilities Sensory disabilities Go-Outside-Home disabilities Individuals without disabilities Age Gender
Dependent variables	Microscopic	Walking speed Walking trajectory Longitudinal spacing Lateral spacing
	Macroscopic	Speed-Density relationship Flow-Density relationship Speed-Flow relationship

2.4. Data collection

In recent years, advances in technologies have assisted researchers to collect accurate behavior data in transportation engineering field (for example see Gong et al., 2012; Jalayer et al., 2015; Baratian-Ghorghi et al., 2015). In this study, a tracking system was developed using an automated video tracking technology to collect walking trajectories. Power-over-Ethernet (POE) cameras were used for tracking purposes. These cameras are compact but have a high resolution of 1280x1024 pixels at a maximum frame rate of 50 fps. For full camera coverage, a c-mount 3.5 mm focal length lens that gives a large area of coverage per camera were selected. Twelve cameras were suspended from steel building girders to provide full coverage of the study area with enough overlap. The tracking system was developed using ARToolKitPlus (ARTKP) (Wagner and Schmalstieg, 2007). ARTKP includes a series of libraries and functions that allow the tracking of up to 512 identifiable markers of known shape and pattern at one time. Markers were mounted on graduation hats and they were assigned to participants. A sample camera, and encoded tracking pattern can be found in Figure 3.

(a) (b)

Fig. 3. Tracking hardware: (a) Power-over-Ethernet camera; (b) tracking marker pattern.

High frame rate led to increased data volume. To store the data, Ethernet cables lead back to three 8-core 32 gb RAM computers with solid state drives to decrease data storage write time. Power to each camera, as well as communication, was handled using Adlink GIE64+ POE PCIe cards. To examine the system accuracy, several ground tests were conducted. A grid mas marked out on the floor of the test area and markers were statically placed on the ground as well. Test participants wore 'marker hats' and walked around within the room, including tracing out their paths on the grid in both directions. Tracked data was compared with the known distances with the walking grid to determine a ground truth. In the most important two dimensions, data is accurate to a region cloud of 7-17cm. For detailed information about the tracking system and technical setup, readers are referred to Stuart et al. (2013) and Stuart (2015). The testing steps of the tracking system included camera calibration, edge detection, and pose detection.

2.4.1. Camera calibration

To optimize tracking accuracy and reduce errors the cameras were calibrated prior to data collection. Camera calibration is a process to determine camera's extrinsic parameters (i.e., position, orientation) and intrinsic parameters (i.e., focal length, lens distortion, skew) to map three-dimensional world to a two-dimensional image. The traditional calibration sequence used for ARTKP is the Matlab Camera Calibration Toolbox. The results of this step are a perspective projection matrix and image distortion parameters of cameras (Wagner and Schmalstieg, 2007). Preliminary tests revealed that distortion existed due to the wide angle lenses chosen for coverage. To overcome the problem, Omni Camera Calibration (OCC) Toolbox for Matlab, which allows for greater distortion and aberration correction, was used. OCC uses a standard calibration planar checkboard and applies multipoint reference checking for camera calibration. Several attempts were made to obtain an error smaller than a 0.5 pixel threshold. After calibration, a static marker position could be identified reliably in a 2-D plane from 5 to 15 cm, depending on distance from the camera (Stuart, 2015).

2.4.2. Edge detection

After sending the captured video to the computer, ARTKP searches through each video frame to detect markers. As shown in Figure 3 (b), each marker is composed of a black border and a pattern. The first step in the tracking process is finding a marker's edges. To this end, ARTKP first thresholds each frame using an adjustable value (i.e., the median of all extracted marker pixels) to produce a black and white binary image. It then searches for quadrangles while removing too large/small areas to finally detect the marker's pattern (Wagner and Schmalstieg, 2007).

2.4.3. Pose detection

In this step, ARTKP uses the marker's edges to detect pose and orientation of each frame. It first estimates the marker's pose matrix using the matrix fitting. ARTKP then determines the transformation matrix from the camera plane to a local coordinate system in the center of the marker. The local coordinates are further used to determine the location of each marker in the video frame (i.e., the Cartesian coordinates of the center pixel of the marker). The resulting coordinates are then written to a text file annotated by marker identifier. Figure 4 presents the steps of tracking system procedure.

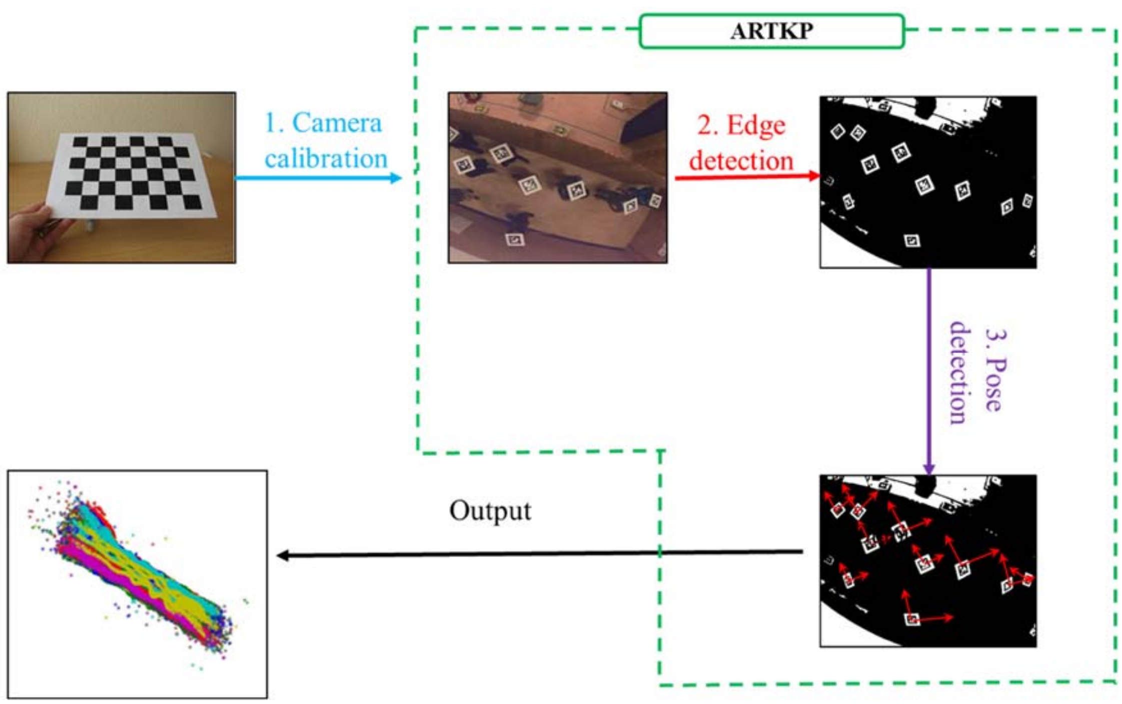


Fig. 4. Steps of tracking system.

2.5. Survey design

A survey questionnaire was employed to examine stated walking behavior. Both pre-surveys and post-surveys were used. The pre-survey instrument included 22 questions (5 short answers and 17 ordered multiple choice questions): Four questions covered personal demographic data (e.g., age, gender, and type of disability); Three questions related to walking habits (average distance a person walks each day, number of days per week a person walks for at least 10 minutes continuously, and purposes for walking [going to work or school, shopping, exercise]); The remaining questions assessed the participant's tactical motivators for walking behavior and interactions with other participants. For example: in a walking facility how likely would you be to (a) follow another individual(s), (b) pass another individual(s), (c) change walking behavior toward another pedestrian with disabilities, (d) be impacted by encountering an individual with disabilities.

Following the experiments, the post-survey instrument included six ordered multiple choice questions used to assess conditions during the experiments and another question to determine the role of perception in the observed pedestrian behaviors. The latter question used six images from the Highway Capacity Manual (HCM) (TRB, 2010) representing different level of service (LOS) conditions. Each of the photos represented different pedestrian occupancy loads, spacing, and flow volume. The participants were asked to select the image that best represented their walking condition. Using revealed behavior and responses to this question we were able to analyze participant perceptions regarding their ability to maneuver and/or negotiate the environment. Participant responses were coded according to common terms (short answer) and ordinal values (Likert-scaled responses) in relation to the spatial location referenced in the participant's response. In this way, participants stated data were compared with the revealed behaviors observed in the spatial location. Survey data were stored in a database in addition to the measured data for more informed analyses of the relationship between components and observed behaviors.

2.6. Pilot test

Prior to beginning the experiments, pilot tests were conducted with people without disabilities to ensure that the tracking errors were in 7-17cm range. Using a large number of people for the pilot tests was helpful in anticipating possible problems in conditions such as congestion. In addition, both pre and post-surveys were reviewed by experts for readability, length, and ability to collect required feedback within the time available. Despite detailed planning and assessment of pilot tests, some organizational or technical aspects could not be predicted. Managing an experiment involving a large number of people without and with disabilities requires a high degree of coordination within the research team. This section narrates the experimental procedures used in circuit and stairway experiments.

3. Principal experiments

The walking behavior or circuit study was conducted over two days (November 9th, and 15th, 2012). The stair experiments were conducted in one day (November 22th). Before conducting the experiments, administrators were delegated specific duties to allow them to manage and direct large numbers of people including individuals with disabilities. For example, someone was responsible for administering surveys and assisting people with disabilities. Another researcher was to control the participant entering and exiting process. This researcher acted like a ramp meter, allowing participants to enter the circuit according to a predefined plan and controlling the number of participants in the circuit.

To minimize the risk of accidental injury or fatigue during the experiments, every participant received safety instructions before the experiments. Researchers then familiarized participants with the environment, explained procedures for entering and exiting the circuit, and instructed them to walk naturally. As the tracking patterns can be hidden if participants remove their hats or tilt their hats and/or heads to far, pictures guides (see Figure 5 below) were hung on the walls of the study area to remind participants to keep their hats in an upright, readable positon.

Fig. 5. Guiding pictures.

To examine different scenarios of flow compositions, the experiments were categorized into two major groups:

1. One-way experiment (i.e., one-directional flow experiments)
2. Two-way experiments with different flow compositions (90% major stream 10% minor stream, 80 major 20% minor, 70% major 30% minor, 60% major 40% minor, and 50% major 50% minor).

Each experiment was divided into ten-minute recording sessions of a single scenario. The circuit experiments required participants to move at their maximum comfortable speed through circuit. There were no special requirements for participants to participate in all sessions and they were instructed to exit the circuit through emergency doors when they felt that it is difficult for them to continue. The ramp meter person gradually injected participants to the circuit. This method made it possible to observe behaviors in a wide range of density levels from free flow condition to highly dense situation.

During the experiments, some of participants were randomly selected by the ramp meter person after their lap completion to answer post-survey questions. After running 10-minute movement period, all participants were asked to exit the circuit and rest prior to the start of another scenario. For the stairwell experiments, two stairways connected by a hallway were used. This made it possible for participants to circulate between the two sets of stairs. The experiment process and surveys used for the stairway experiments were exactly the same as the circuit experiments except for the necessary exclusion of wheelchair users. Figure 6 presents a snapshot of circuit experiments.

4. Methods

Collected walking trajectory data can be used to extract the primary microscopic variables, walking speed and spacing, considered two of the most important variables affecting the design of walking infrastructure. To extract walking speed, the position of each participant was recorded every second and walking distance was determined using these recorded positions. Walking speed was computed by dividing the walking distance by the time duration between the recorded start and end positions of the walking distance. To compare mean walking speed of individuals with and without disabilities, the following null hypothesis can be examined:

Hypothesis 1. There is no significant difference in the mean walking speed (μ) between individuals without disabilities and individuals with disabilities in various walking facilities (passageway, oblique angle, right angle, and bottleneck).

H^1_n: $\mu_{\text{individuals with disabilities}} = \mu_{\text{individuals without disabilities}}$
H^1_a: $\mu_{\text{individuals with disabilities}} < \mu_{\text{individuals without disabilities}}$

Walking speed of individuals without disabilities were extracted from one-directional homogeneous experiments and the speed of individuals with disabilities were computed from one-directional heterogeneous experiments. Four classifications of individuals with disabilities were examined: individuals with visual impairments, individuals who use mobility canes, individuals who use non-motorized devices for walking (e.g., wheelchair/roller walker), and individuals using motorized wheelchairs. Specifically, six individuals with visual impairments (three males, three females), three individuals with mobility canes (three males), four individuals with non-motorized devices (one male, three females), and six individuals with motorized wheelchairs (three males, three females) took part in the experiments reported here.

Spacing between individuals is another microscopic variable reflecting individuals' interactions. Using the trajectory data, spacing between each participant and individuals who are within defined lateral and longitudinal boundaries were computed for each time frame (i.e., 0.02 sec). Boundary dimensions were selected based on Fruin's suggestion (0.7 meter for lateral and 2.4 meter for longitudinal) (Fruin, 1971). The following null hypothesis was studied to compare mean spacing for different individual types:

Hypothesis 2. There is no significant difference in the mean spacing (S) for individuals without disabilities and individuals with disabilities.

H^1_n: $S_{\text{individuals with disabilities}} = S_{\text{individuals without disabilities}}$
H^1_a: $S_{\text{individuals with disabilities}} > S_{\text{individuals without disabilities}}$

Similar to the first hypothesis, only one-directional scenarios were examined.

5. Results and discussions

Mean walking speeds of different individuals were statistically compared using analysis of variance (ANOVA) as the independency and normality conditions were met. The data is from observations of independent individuals, meeting the first condition. To check the normality assumption, normal Q-Q plots were examined as shown in Figure 7. These plots present the quantiles of the observed data against the quantiles of normal distribution. The presented Q-Q plots for walking speed of different individuals in the passageway (Figure 7) demonstrate that the observed points roughly follow the reference line indicating that the normality assumption was met.

Figure 8 presents trajectories for sample individuals and results of hypothesis testing. Tables in this figure include walking speed descriptive statistics including number of observation (N), mean speed, standard deviation (STD), p-values, and hypothesis test results. The obtained mean walking speed for the passageway were comparable to the findings in Boyce et al. (1999c). The study evaluated movement speed of 155 individuals on level surfaces and they reported that wheelchair users moved through the horizontal section at mean speeds of 0.89 m/s and 0.69 m/s for electric wheelchair users and manual wheelchair users, respectively. Results indicate that all p-values were lower than 0.01, showing that walking speeds of individuals with disabilities were significantly lower than individuals without disabilities in all walking facilities. Therefore, the first null hypothesis was not supported.

This suggests that design plans based on walking speed of individuals without disability may overlook vulnerable walker needs. Among individuals with disabilities, individuals with visual impairments generally had higher mean walking speeds in all facilities suggesting that physical impairments are more restrictive. Also, results show that the speed of individuals were reduced by the complexity of walking facilities. Although slight turning in oblique angles didn't show substantial impact on walking speed, all individuals had their minimum speed in bottleneck and right angle facilities, indicating that space restrictions and complex turning movements can significantly reduce walking speed and should be considered in design process. These findings are consistent with the study by Clark-Carter et al. (1986) who found that the walking speed of individuals with visual impairments was significantly reduced by the complexity of the built environment. For deeper analysis, readers are referred to studies by Sharifi et al. (2015c), and Sharifi et al. (2015d).

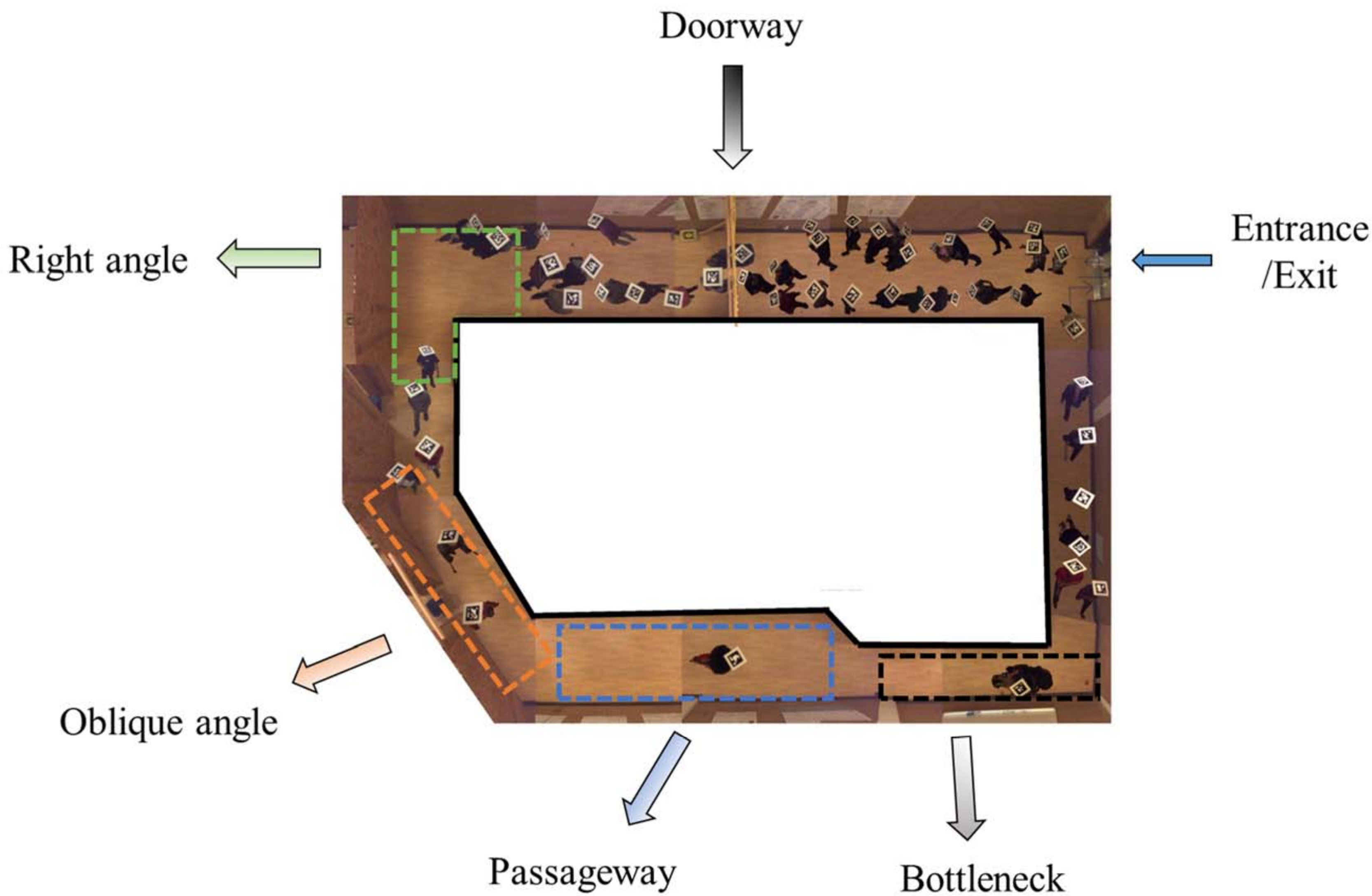


Fig. 6. Snapshot of circuit experiment**.**

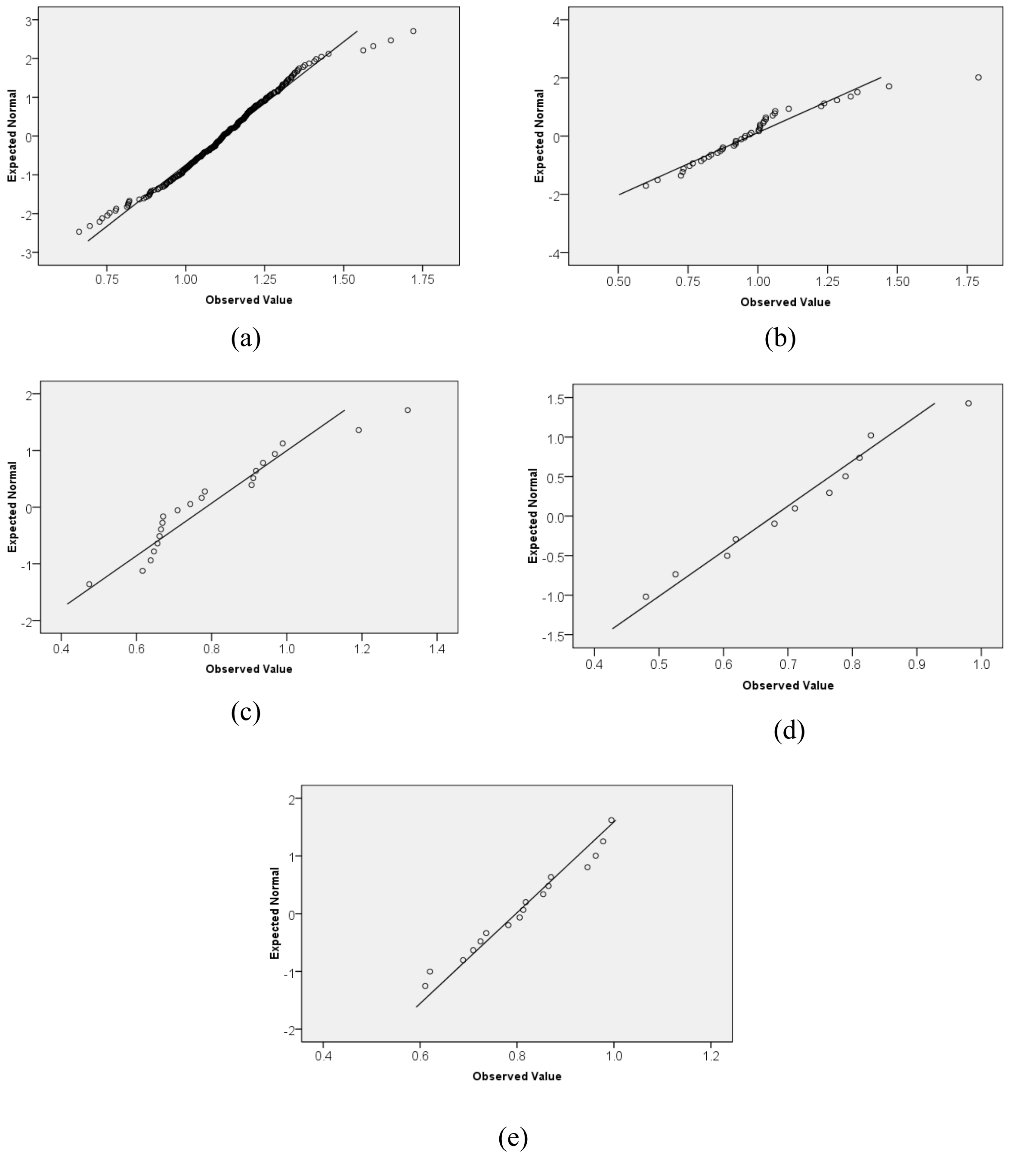
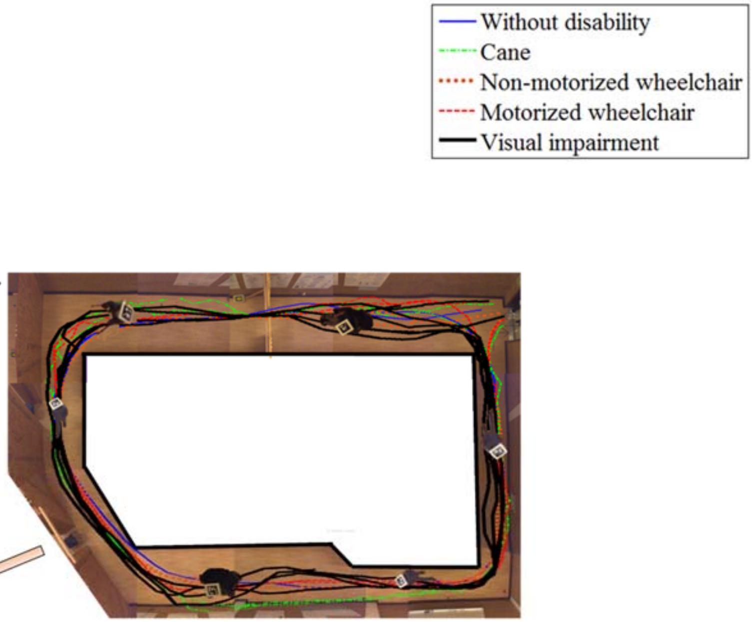


Fig.7. Walking speed Q-Q plots for: (a) individuals without disabilities; (b) visual impairments; (c) motorized wheelchair; (d) non-motorized wheelchair; (e) individuals with cane.

Right angle

Individual type	N	Mean speed (m/s)	STD (m/s)	*p*-value	H^1_n
Without	293	0.91	0.18	-	-
Visual	46	0.82	0.21	< 0.01	Reject
Motorized	25	0.75	0.15	< 0.01	Reject
Non-motorized	15	0.56	0.15	< 0.01	Reject
Cane	20	0.59	0.11	< 0.01	Reject

N: Number of observations; STD: Standard deviation



Oblique angle

Individual type	N	Mean speed (m/s)	STD (m/s)	*p*-value	H^1_n
Without	295	1.12	0.24	-	-
Visual	45	0.96	0.32	< 0.01	Reject
Motorized	23	0.78	0.26	< 0.01	Reject
Non-motorized	13	0.69	0.17	< 0.01	Reject
Cane	17	0.75	0.25	< 0.01	Reject

N: Number of observations; STD: Standard deviation

Bottleneck

Individual type	N	Mean speed (m/s)	STD	*p*-value	H^1_n
Without	199	1.03	0.19	-	-
Visual	48	0.8	0.2	< 0.01	Reject
Motorized	24	0.67	0.19	< 0.01	Reject
Non-motorized	11	0.7	0.12	< 0.01	Reject
Cane	18	0.75	0.17	< 0.01	Reject

N: Number of observations; STD: Standard deviation

Passageway

Individual type	N	Mean speed (m/s)	STD (m/s)	*p*-value	H^1_n
Without	294	1.12	0.16	-	-
Visual	45	0.97	0.23	< 0.01	Reject
Motorized	22	0.78	0.21	< 0.01	Reject
Non-motorized	12	0.68	0.17	< 0.01	Reject
Cane	18	0.8	0.13	< 0.01	Reject

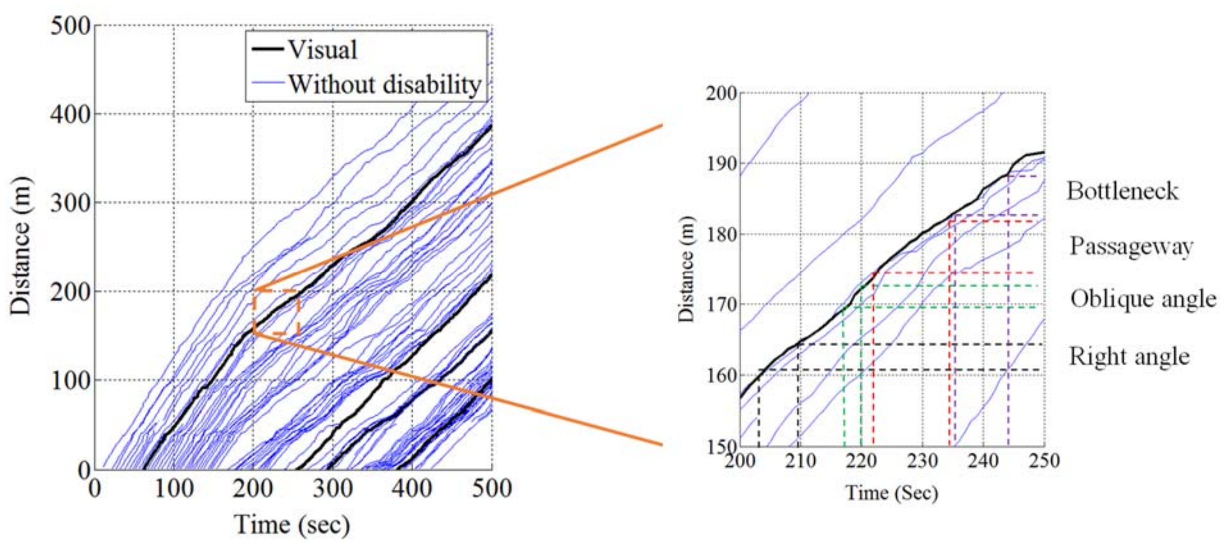
N: Number of observations; STD: Standard deviation

Fig. 8. Trajectories and walking speed analysis.

Spacing between individuals with and without disabilities can be visualized using time-space trajectories. Time-space diagrams show the position of each participant against time indicating how participants manage their speed and spacing when they walked through the circuit. Time-space diagrams for different individuals are presented in Figure 9, with the vertical distance between two consecutive lines showing spacing between pedestrians.

Spacing for different individual types were computed for each time frame and ANOVA was conducted to compare spacing for different individual types. Figure 10 presents the Q-Q plot for spacing of different individuals in the passageway. It can be observed that the points don't heavily deviate from the reference line indicating that the normality assumption was met. Table 3 presents basic statistics including number of observations, mean, standard deviation and results of hypothesis testing. Results revealed that except individuals with visual impairments, all other disabled group were more conservative and maintained higher space from front individuals in all walking facilities. All p-values comparing these groups were lower than 0.01 indicating that the differences in behaviors are statistically significant. This suggests that individuals with disabilities need more space to maintain their speeds and designers should consider that in their plans. Results show that individuals with visual impairments maintained less spacing comparing with other disabled types, suggesting that perhaps visual perception is an important component of interpersonal spacing dynamics.

Individuals with motorized wheelchairs generally kept more spacing in all facilities. This finding might be linked to the specifications of motorized wheelchairs where the mechanical constraints and/or individual's impairments may create some manoeuvring difficulties which lead individuals using wheelchairs and those around them to maintain greater distances to prevent collisions, particularly in dense environments. Table 3 also show that interpersonal spacing dynamics changed with respect to facility configurations. While individuals generally maintain their spacing in the passageway and oblique angle, spacing substantially drops in bottleneck and right angle facilities. This suggests that individuals are more constrained in narrow spaces and turning areas. Therefore, providing more space in walking infrastructures with complex geometries may be require to meet needs of different individual types.



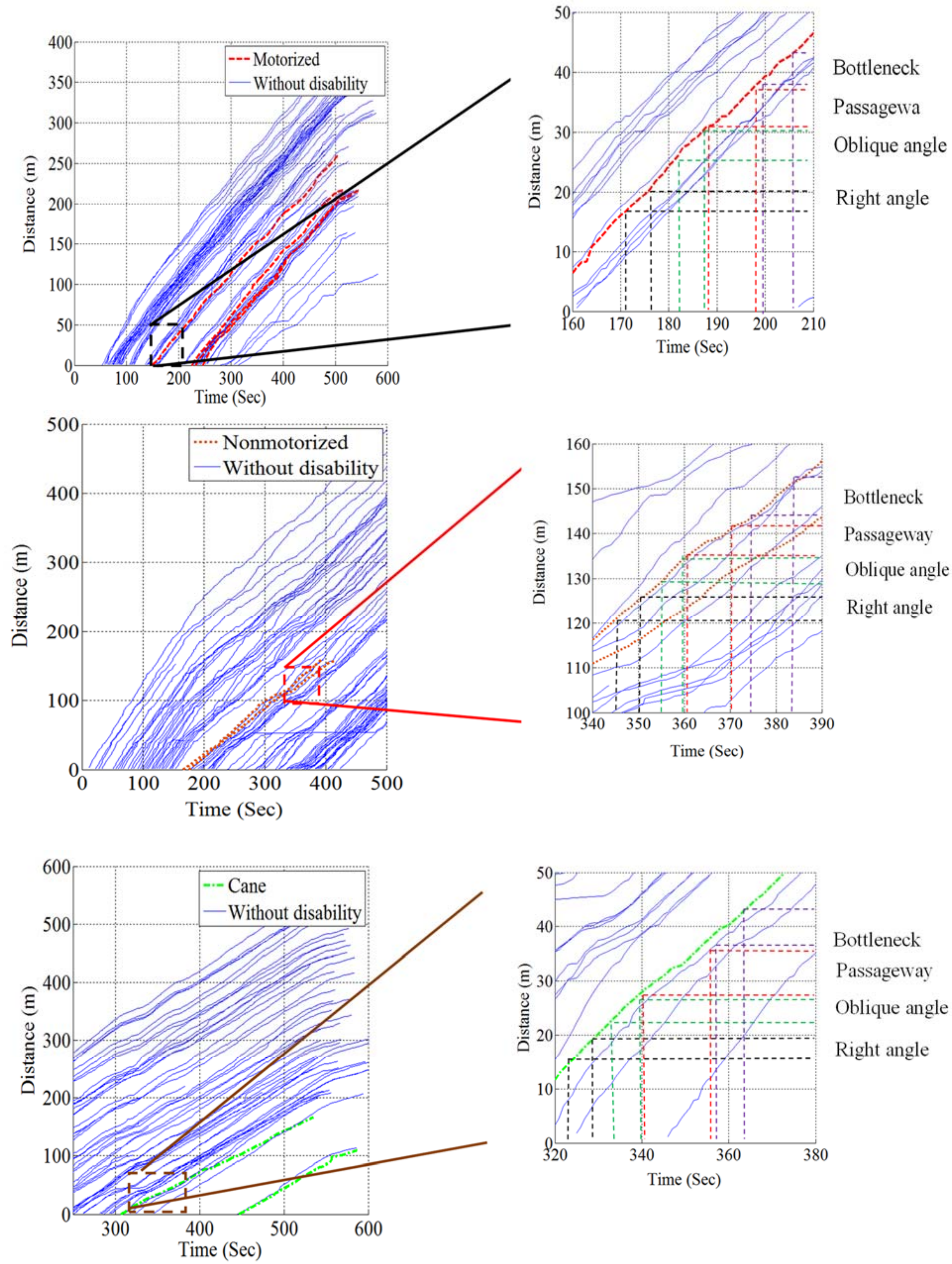


Fig. 9. Time space diagrams.

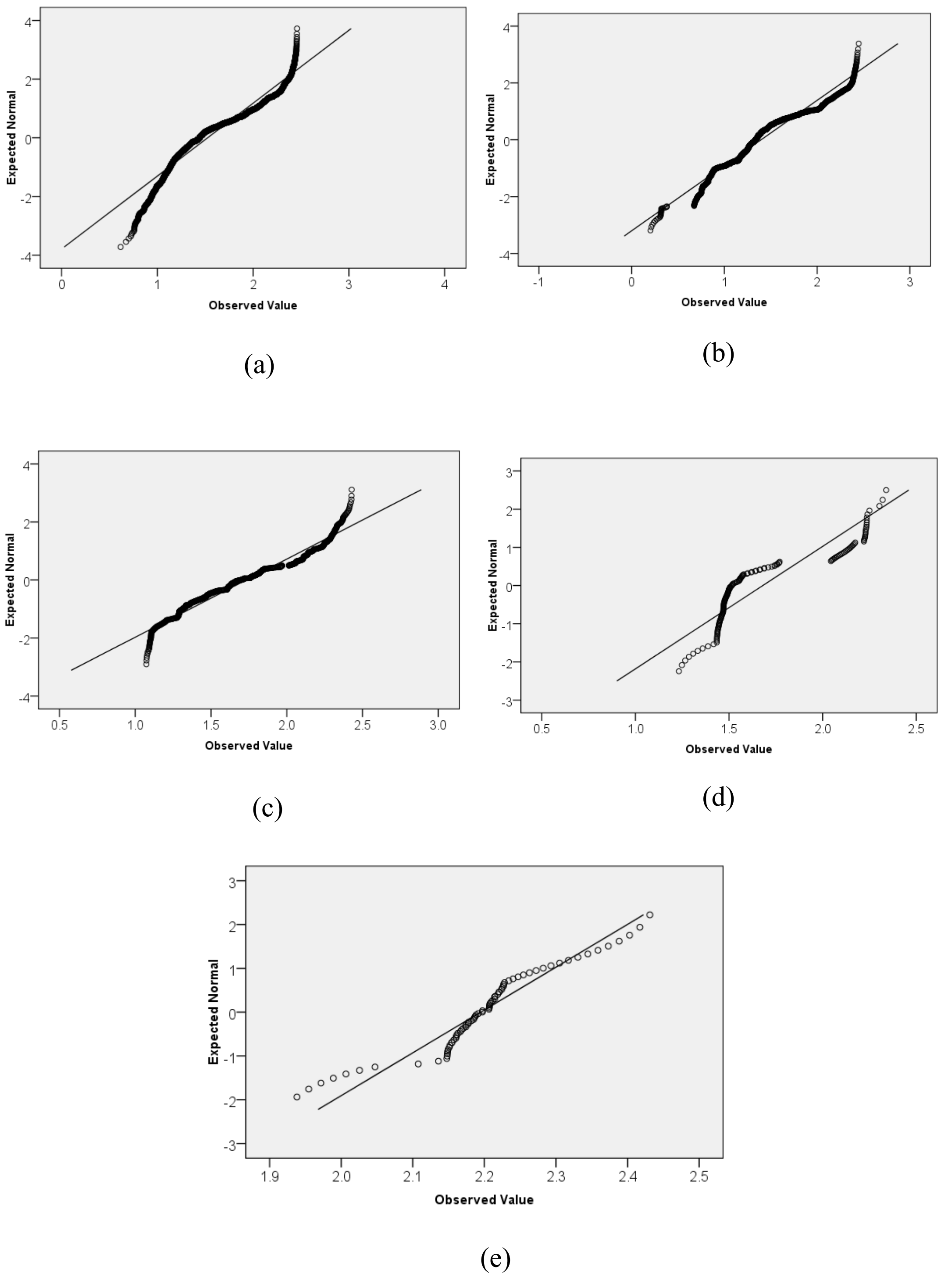


Fig.10. Spacing Q-Q plots for: (a) individuals without disabilities; (b) visual impairments; (c) motorized wheelchair; (d) non-motorized wheelchair; (e) individuals with cane.

Table 3. Spacing statistical analysis.

Individual type	N	Mean (m)	Std (m)	*p*-value	H^1_n
	Passageway				
Without disabilities	10149	1.52	0.4	-	-
Visual	2802	1.39	0.43	< 0.01	Reject
Motorized	1082	1.73	0.37	< 0.01	Reject
Non-motorized/walker	160	1.68	0.31	< 0.01	Reject
Cane	76	2.19	0.1	< 0.01	Reject
	Bottleneck				
Without disabilities	6588	1.2	0.35	-	-
Visual	2936	1.15	0.36	< 0.01	Reject
Motorized	754	1.73	0.26	< 0.01	Reject
Non-motorized/walker	87	1.38	0.4	< 0.01	Reject
Cane	492	1.27	0.31	< 0.01	Reject
	Oblique angle				
Without disabilities	18132	1.45	0.44	-	-
Visual	3117	1.46	0.4	0.1	No Reject
Motorized	1638	1.75	0.32	< 0.01	Reject
Non-motorized/walker	281	1.75	0.3	< 0.01	Reject
Cane	310	1.67	0.32	< 0.01	Reject
	Right angle				
Without disabilities	9449	1.18	0.39	< 0.01	-
Visual	2833	1.2	0.39	< 0.01	Reject
Motorized	545	1.8	0.32	< 0.01	Reject
Non-motorized/walker	121	1.64	0.39	< 0.01	Reject
Cane	429	1.4	0.24	< 0.01	Reject

6. Implications

This paper presents an overview of a controlled large-scale study of the walking behaviors of individuals with different types of disabilities, including the experimental procedure before and during the experiments. Before beginning the principle experiments the most important steps to be completed by the research team members are identifying variables of interest and a suitable measurement method, selecting an appropriate study site, developing the automated tracking system, recruiting participants, and designing the survey instruments. Experimental design and processes are explained in the during experiments section. The available data, which represents the most extensive examination of the walking behavior of pedestrian groups involving individuals with disabilities, is substantial and warrants further research to advance our empirical understanding of the pedestrian behaviors of individuals with disabilities. Using the collected data, studies are underway to investigate that how walkways, stairways, queuing areas (e.g., doorways), and direction changes in the built environment affect the walking behaviors of diverse individuals. The results of the research informs current understanding of pedestrian walking behaviors involving individuals with disabilities. Specifically, research outcomes can support improved practices for the design and renovation of built environments as follows:

Urban and building design. The collected data will help designers understand the user/occupant of the designed environment and test the design layout to determine how well it meets the needs of the occupant prior to construction while changes in design are possible.

Individuals with disabilities' movement patterns, and their interactions with environments and other pedestrians can largely determine the effectiveness of the design. Further, buildings' interior layouts may involve complex geometries, such as different angles, which should be designed to operate at a satisfactory level. Unfortunately, most existing public building design guidelines, found in the Highway Capacity Manual (HCM) (TRB, 2010) and the International Building Code (IBC) (ICC, 2012), fail to offer adequate consideration for individuals with disabilities. To account for the needs of individuals with disabilities, the Americans with Disabilities Act Accessibility Guidelines (ADAAAG, 2002) provide guidelines for the design of pedestrian facilities. This code is based only on physical properties and it does not consider the interactions between people with and without disabilities. The rich data set make it possible to overcome the practice limitations. For example, walking trajectories of individuals with disabilities can be studied to determine minimum required space to negotiate different walking facilities in various occupant load levels.

Directly, the results of this study suggest the urban designers, architects, and engineers that design plans based on the walking speed of individuals without disability, or the existing guidelines which do not reflect the heterogeneity of pedestrians, may overlook vulnerable walker needs, as well as creating environments which create walker vulnerability. Complex geometries can significantly reduce the walking speed of heterogeneous populations and urban designers, architects, and engineers should providing more space in walking infrastructures with complex geometries to meet needs of different individual types. Similarly, individuals with disabilities need more space to maintain their preferred speeds, which designers should consider in their planning efforts. The HCM guideline suggests that a minimum of 1.2 m^2/p space is required for pedestrians to reach to their desired speed. But the guideline doesn't provide any requirements for individuals with disabilities. The minimum required space for these individuals can be estimated from the observed lateral and longitudinal spacing. Results revealed that the minimum space in a passageway for individuals with either motorized or non-motorized wheelchairs should be approximately 1.73 m^2/p (a 36% increase) and 1.68 m^2/p (a 33% increase), respectively.

Transportation engineering / policy. Exploring the data can enhance current practices in transportation engineering. For example, pedestrian walking speed is widely used as input for many transportation engineering applications, such as determining required gap sizes and pedestrian signal timing (Arango and Montufar, 2008). Currently, walking and building design manuals do not differentiate between different walking geometries. The findings of this research can improve the current knowledge and it can help to develop efficient designed plans. Further, given the complexity of walking behavior, one of the most widely applied methods for pedestrian behavior modeling and design evaluation is microsimulation modeling (Christensen et al., 2013). Many studies used the approach for many applications including signalized crosswalks evaluations (Lu et al., 2015), pedestrian queuing modeling (Kim et al., 2013), and pedestrians' crossing behavior modeling (Lee and Lam, 2008). Current microsimulation models either do not address individuals with disabilities in their simulated populations or simulate 'standard' individuals with disabilities, giving little emphasis to the largest minority demographic of populations, individuals with disabilities. Participants' movement data can be analyzed along with that of the crowd using the collected data. Thereby, microsimulation approaches testing pedestrian facilities may be enhanced to determine how will these facilities meet their intended requirements and reflect occupants with disabilities. The research findings can help public policy professionals to provide better performance measures to evaluate walking infrastructures. Specifically, walking trajectory data can be coupled with recorded surveys to explore that how individuals with disables perceive the performance of provided facilities. Considering heterogeneous population perceptions can help policy makers to make better decisions on allocating recourses to improve walking infrastructure performances. Further, safety of all pedestrian groups should be considered in strategic plans (Pour-Rouholamin and Zhou, 2016). The results of the research may be used to improve best practices for the design of safer walking infrastructures for pedestrians with disabilities.

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