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Experimental Study on Pedestrian Walking Characteristics through Angled Corridors

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Abstract

Major public infrastructures are increasingly visited by masses of people, not only during special events but also for daily activities. It is extremely important to ensure the safety of these crowds in case of an emergency and to guarantee efficient and bottleneck-free movements in day-to-day situations. A proper understanding of crowd dynamics is vital in order to achieve safety and efficiency at mass gathering places.

Building designers and crowd managers have to rely on microscopic and macroscopic pedestrian crowd simulation models, most of the times, to assess the designs or manage crowds, particularly at public buildings. Further, these models are helpful in identifying problematic places or dangerous spots and to assess and suggest design solutions for crowd gathering places. However, in order to calibrate and validate these explanatory models for complex pedestrian movements, such as turning movements, and to gain more insights in to pedestrian behaviours, detailed empirical data are required.

A series of experiments with a group of pedestrians were conducted recently at Monash University to understand the microscopic walking characteristics of individuals walking through angled corridors. Initial results suggest that, angles of more than 90° can significantly decrease the free flow walking speeds of individuals. This threshold angle can be reduced up to 60° when pedestrians' desired speed is high.

1. Introduction

1.1 Motivation

Large crowds can be expected at public spaces whenever there are special events, such as religious, cultural, or sporting events. Designing such public buildings and crowd gathering places and, planning those places for special events are challenging tasks, because it is extremely important to evacuate those crowds efficiently and ensure their safety in case of an emergency. As can be understood from the International Crowd Disasters web site (Still 2013), enhancing safety at mass gathering places during emergencies is still a difficult task. Not only during emergencies, but also during day-to-day activities (for example in transfer stations), it is important to guarantee efficient and congestion-free crowd movements.

In order to achieve these broad objectives, building designers and crowd managers can utilise pedestrian crowd simulation tools. However, the reliability of such tools is questionable most of the time, because those are required to be calibrated against reliable empirical data and ensure the validity, before putting it in to practice. For model calibration and validation purposes, empirical data can be collected through real world observations or controlled experiments. Although real world observations provide bias-free data, it is very difficult to capture specific situations for a number of times under the same conditions in the real world. Therefore, controlled experiments are more common than real world data, as experiments can be conducted under various conditions and can be repeated under the same conditions. Not only for model calibration and validation purposes, but these empirical data are also vital in order to improve the knowledge related to pedestrian dynamics and to gain more insights into microscopic human walking characteristics.

Various behavioural phenomena have been experimentally verified by previous authors. For example, crossing or intersecting pedestrian flows (Asano et al. 2007, Wong et al. 2010, Daamen and Hoogendoorn 2003, Helbing et al. 2005), T-junctions (Boltes et al. 2011, Zhang et al. 2011) and walking through narrow bottlenecks (Daamen and Hoogendoorn 2003, Helbing et al. 2005, Tobias et al. 2006) are famous among those studies. However, a major gap in the knowledge is that there are very few studies that have considered the effect of turning angle on human walking behaviours. Among those studies, almost none have examined the impact on different turning angles on microscopic walking characteristics. Further, less attention has been given to solo or free-flow speed distributions, even though the free flow speed is an important parameter in many simulation models (Daamen and Hoogendoorn 2007). Studying solo or individual walking characteristics could be useful for deriving and calibrating parameters or behavioural rules for microscopic pedestrian simulation models (Brogan and Johnson 2003), in which individual agents are treated as separate entities and therefore each of them has their own status and rules. In order to address those gaps in the knowledge, a series of experiments were designed and the initial set of those were conducted. Details of those experiments, data extraction methods and some initial results related to solo walking are discussed in this paper.

1.2 Objectives

The main objective of this study is to quantify the effect of turning angle on solo (or unhindered) and collective walking characteristics. Data were collected through a series of experiments conducted with a group of humans walking under different conditions.

Another objective of this experimental study is to collect data to calibrate the microscopic pedestrian simulation model (EmSim) developed at the Institute of Transport Studies at Monash University (Shiwakoti et al. 2011) for more complex situations. The initial version of this model successfully predicts the collective escape behaviour under normal as well as panic conditions for fundamental situations. However, that initial model must be modified and calibrated to capture more complex situations. The data collected through these experiments will be utilised for that purpose as well at a later stage.

The paper is structured as follows: The next section (Section 2) briefly discusses several previous studies that considered walking on angled or curved paths. That is followed by the Section 3 that describes the experiments carried out and the method of data extraction. Then an overview of the results of these experimental studies is provided under Section 4. Finally, conclusions and recommendations for further studies are presented.

2. Walking on Angled or Curved paths

Influence and consequences of turning movements on individuals' walking have been discussed in several previous studies. Yanagisawa et al. (2009) mentioned that the walking speed decreases when the angle of deviation from the former direction of motion increases due to the effect of inertia. In order to incorporate the effect of turning on walking speed, they introduced a linearly decreasing function that was called the turning function in their cellular automata (CA) model.

Courtine and Schieppati (2003a and 2003b) experimentally demonstrated that that when humans walk on curved paths, the mean body velocity decreases. They pointed out that, on average the velocity was significantly lower when walking along curved rather than straight paths under normal walking conditions and with or without vision. One major reason for this, as they established, was the disequilibrium of the body, head and limbs during the turning locomotion. Although they have not specified the turning angle of the curved path, it was apparently more than 90° according to locomotor tra jectories.

As verified by (Vieilledenta et al. 2001, Gribble and Ostry 1996 and Ivanenko et al. 2002), the relationship between the curvature of the path and the walking speed is planned by the central nervous system and can be described mathematically with one-third or two-third power law. That is, the tangential velocity is proportional to the one-thirds root of the curvature, or the angular velocity is proportional to the two-thirds root of the curvature.

According to experimental findings by Hicheur and Berthoz (2005), humans adapt their locomotion patterns considering centrifugal acceleration when walking on curved paths. As they verified, the reduced speed provides a more stable frame for the body to steer along the curved path. Not only centrifugal acceleration, but also asymmetries and unbalance in the body trunk, limbs and head can also be minimised by reduced speed along curved paths as experimentally established by Hicheur et al. (2005) and Imai et al. (2001). Therefore the reduced speed on curved paths allows pedestrians to negotiate the curve smoothly and efficiently.

It can be noted that almost all of the above described studies, which mainly belong to neurology or brain sciences, consider the changes in physiological responses (such as head and limb movements) rather than microscopic walking characteristics. The few available studies, such as (Steffen and Seyfried 2009), have confined to one case (for example 90° turnings) and have given priority to qualitative examinations rather than quantitative analysis. Thus, it is clear that there are major gaps in the knowledge regarding microscopic walking characteristics on angled pathways.

Assessing impacts of turning angles on human walking speeds will be beneficial in many aspects, such as determination of unexpected delays (can be combined with the level of service) of walking facilities, estimating transfer times from one service to another service at transfer stations (that can be helpful in time tabling purposes as stated in Daamen and Hoogendoorn 2007), and estimating evacuation times at public buildings and so on.

In order to quantify the effect of various turning angles on walking characteristics (mainly on the walking speed) and to collect data for model calibration and validation purposes, a series of experiments were designed and conducted at the Department of Civil Engineering of Monash University. Details of these experiments are described in the next section.

3. Experiments

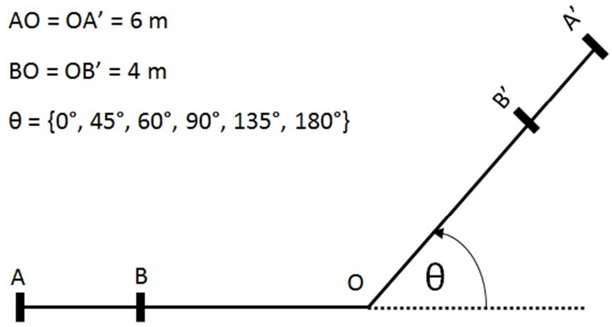
3.1 Sample

The experiment was performed at an open space on 5 weekdays in April 2013, with 16 participants (11 males and 5 females) who were postgraduate students and whose ages ranged from 26 to 33 years. These experiments were conducted in accordance with the guidelines by the Human Research Ethics Committee of Monash University.

3.2 Experiment setup and scenarios

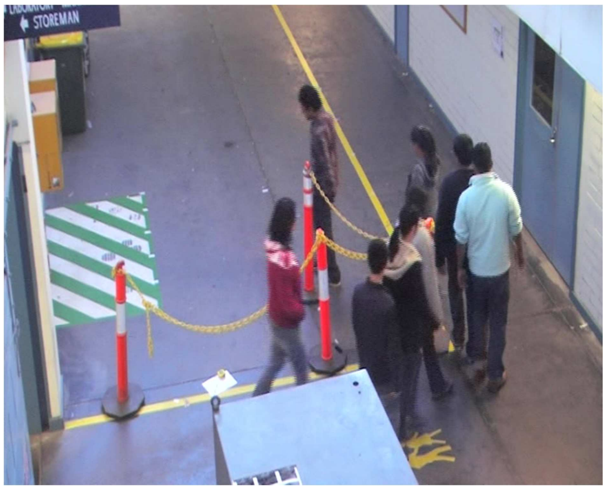
The purpose of this series of experiments is to quantify the effect of turning angle on human walking characteristics under different conditions, i.e. under unhindered (or solo) walking conditions, under the influence of surrounding pedestrians (interpersonal interactions), under the effect of blocked vision (due to walls) and under the influence of confronting pedestrians (two way pedestrian traffic). Starting with the simplest system, this paper investigates the effect of different turning angles on solo walking. The schematic diagram of the walking path is depicted in Figure 1, along with snapshots taken during the experiment. Note that, in order to reduce the degrees of freedom, the effect of blocked vision (due to walls) was deliberately excluded by setting out the angled corridors only with safety barriers and chains (see Figure 1). The remaining set of experiments that will investigate the combined effect of turning angle, confronting pedestrian flows and blocked vision (and that will utilise movable walls to set out the angled paths) will be carried out in the future.

Figure 1: (a): Schematic diagram of the walking path with dimensions, (b) and (c): Snapshots during the solo and collective walking experiments under normal walking conditions for 135° turning angle



(a)

(b)



(c)

Five turning angles, namely 45°, 60°, 90°, 135°, 180° were considered along with a straight walking case (i.e. 0° turning angle). Further, two different (randomised) walking speeds, i.e. normal and fast, were considered. All scenarios completed to date are summarised in Table 1.

Table 1: Experiment scenarios

		Turning angle					
		0°	45°	60°	90°	135°	180°
Solo*	Normal speed§	√	√	√	√	√	√
	Fast speed¥	√	√	√	√	√	√
Collective¤	Normal speed	√	√	√	√	√	√
	Fast speed	√	√	√	√	√	√

*One person walking at a time, ¤8 people walking together as a group, §Walking speed is approximately 1.44 m/s, ¥Walking speed is approximately 2.00 m/s

3.3 Experimental procedures

Without revealing any information regarding the purpose of the experiment, participants were instructed as described briefly in Table 2.

Table 2: Experiment procedures and instructions

Experiment	Procedure and instructions
Solo walking at normal speed	Participants were instructed to walk on the angled path at normal walking speed, one by one (see Figure 1 (b))
Solo walking at fast speed	As 'fast' is a relative property, participants were instructed to rush through the angled path but not to run.
Collective walking at normal speed	Groups of 8 people were formed and were instructed to walk together at normal speed (see Figure 1 (c))
Collective walking at fast speed	People in groups were instructed to rush through the angled path but not to run.

In order to minimise the effect of the tiredness of participants and to randomise the walking behaviours, participants were divided in to 2 groups before conducting each of those collective walking experiment. All experiments were repeated at least 4 times in order to obtain an adequate sample size.

The entire series of experiments were video recorded with an unobstructed digital video camera pointed from an elevated location. An image sequence was obtained from these videos recordings for the purpose of extracting coordinates. Results obtained thorough analysing these image data are discussed in the next section.

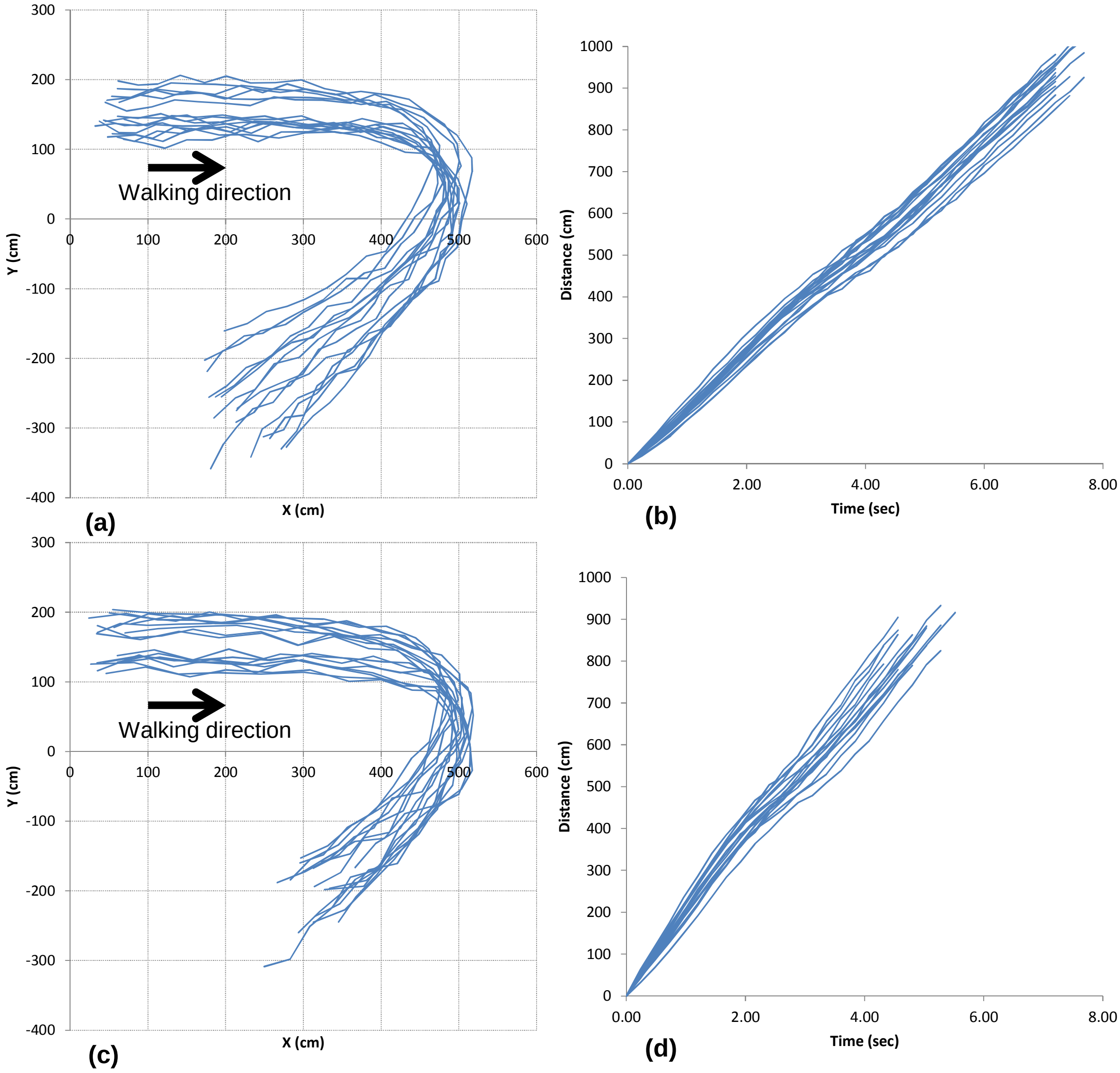
4. Results

4.1 Trajectories

The positions of each pedestrian's heads at 0.24 second intervals were obtained from the image sequence. In order to convert the image coordinates obtained using the oblique camera to ground coordinates, a two-dimensional simultaneous projective transformation (Wolf and Dewitt, 2000) was applied. With the transformed coordinates, trajectories of each individual for all cases were constructed and those for 135° turning angle (for both normal and fast speed cases) are depicted in Figure 2.

From individuals' coordination (Figure 2 (a) and (c)), it can be understood that pedestrians tend to move towards the inner corner when they traverse through angled corridors, which reflects the choice of the shortest route to the destination. This behaviour could introduce additional delays when a crowd walk through an angled pathway. This is because as people move towards the inner corner, the innermost pedestrian lanes could be blocked by outer pedestrian lanes. According to the individual trajectories (Figure 2 (b) and (d)), it can be understood that the normal walking speed is dropped when a pedestrian traverses through higher angled paths, and that drop is magnified when the desired walking speed is high.

Figure 2: Coordination and trajectories for 135° tu rning angle; (a) and (b) – for normal speed walking, (c) and (d) – for fast speed walking



4.2 Free flow walking speed

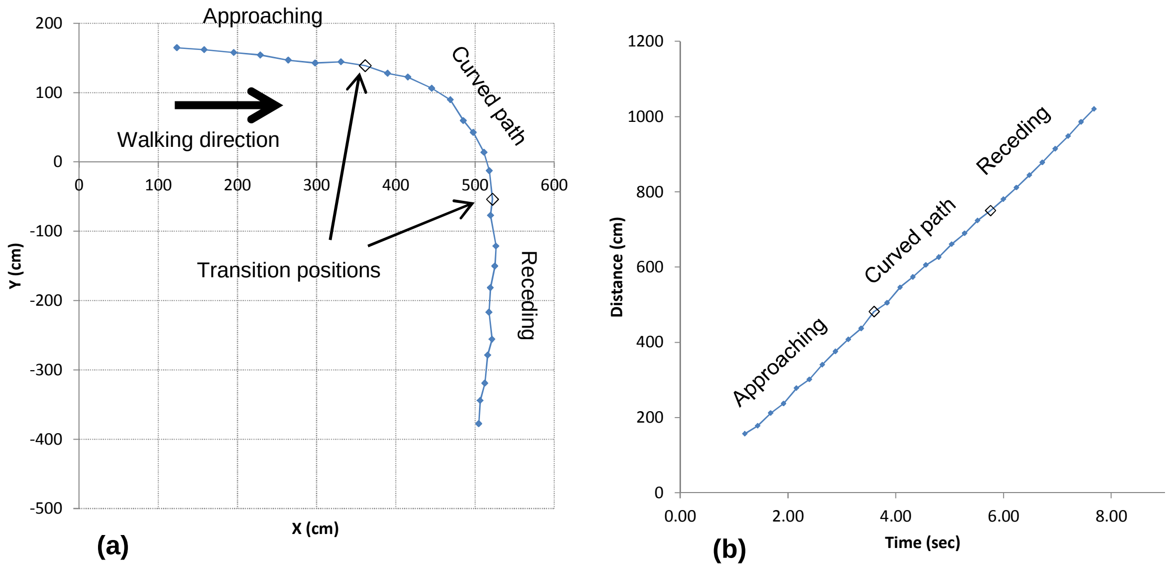
From the trajectories corresponding to the straight walking (0° turning angle) case, free flow walking speed under normal conditions were estimated as 1.44 m/s (SD = 0.18). This value lies within the ranges of free flow speeds estimated in previous studies. For example, the ranges for free flow speed are [0.97 m/s, 1.65 m/s], [1.08 m/s, 1.60 m/s] and [0.85 m/s, 1.55 m/s] according to Weidmann (1993), Daamen and Hoogendoorn (2007) and, Bohannon and Williams Andrews (2011) respectively.

Further, the free waking speed of individuals when they walk 'fast' (for example when people are in a rush or when they are nervous) was estimated as 1.98 m/s (SD = 0.17). As can be understood from the experimental studies conducted by Long and Srinivasan (2013) and Olivier and Cretual (2009), the upper bound of human walking speed can reach up to around 2 m/s, the consistency of the estimated value for 'fast speed' under this study can be confirmed. Although this is a highly relative value, it could be useful as an input parameter in simulation models that consider different levels of nervousness and panic.

4.3 Effect of turning angle on approaching speed

In order to understand and quantify the effect of the turning angle on approaching speed, when an individual is walking towards a corner, the approaching speeds, speeds on curved path and receding speeds were compared. Approaching, curved path walking and receding components of the walking trajectory was determined considering individuals' positions along the walking stretch (Figure 3(a)). From this figure, based on the change in the walking direction, it is possible to approximately determine positions where individuals make the transition from walking a straight path to a curved path and vice versa.

Figure 3: (a) – Transition positions of the walking path (for 90°turning), (b) – Corresponding points on the trajectory



The instantaneous tangential speed of an individual *i* at time *t* was calculated with the equation $v(t) = \sqrt{\dot{x}(t)^2 + \dot{y}(t)^{\,2}}$. Then, these instantaneous speed values correspond to 'approaching', 'curved path' and 'receding' components were separately averaged to obtain average approaching, curved path and receding speeds for each individual. The resulting average speed values (± SD) for normal speed walking cases and high speed walking cases are depicted in Figure 4 and Figure 5 respectively.

Figure 4: Comparison of curved path speed with approaching and receding speeds for normal speed walking

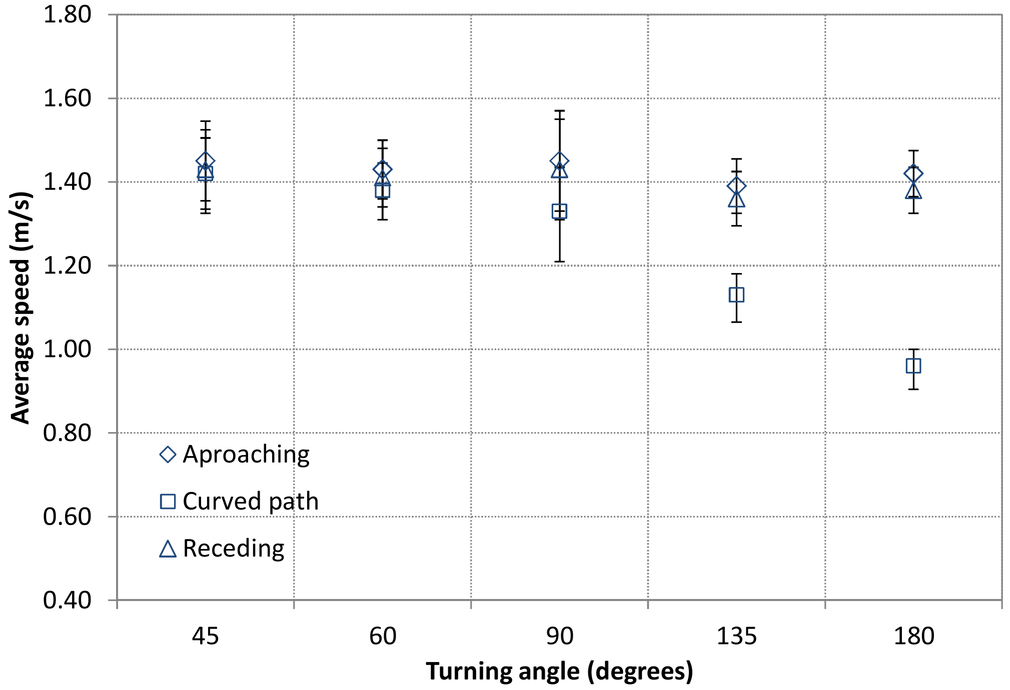
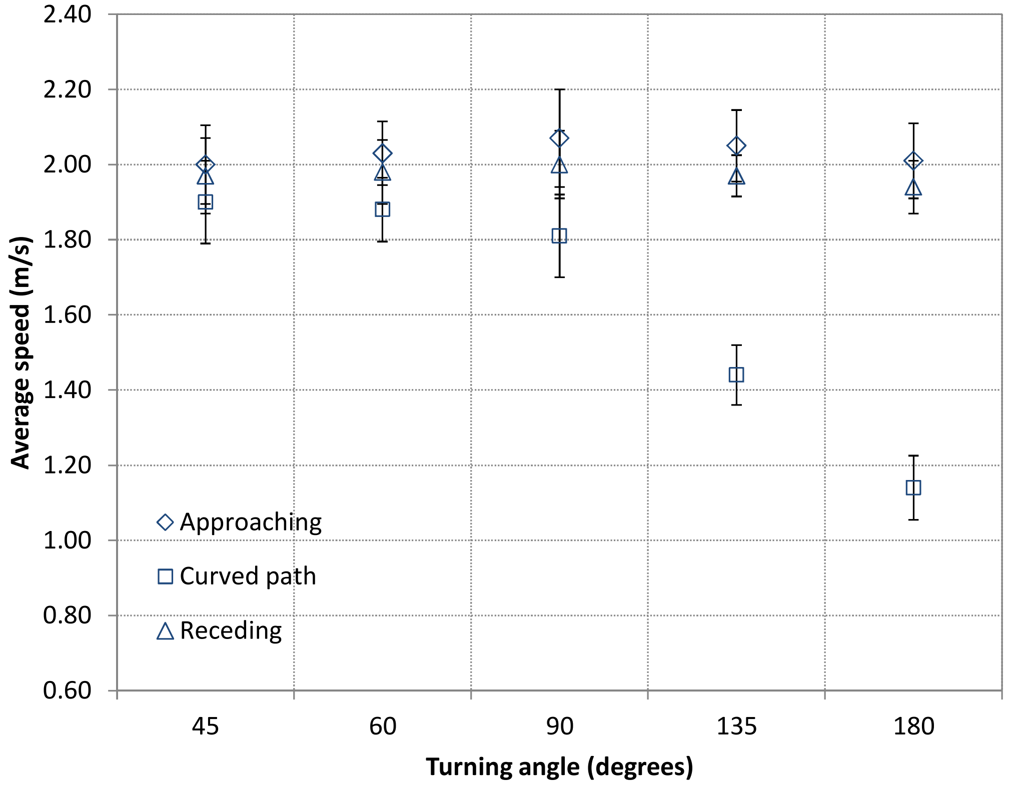


Figure 5: Comparison of curved path speed with approaching and receding speeds for fast speed walking



From Figure 4 and Figure 5, it is clear that approaching speeds and receding speeds are approximately similar for all cases, while they are always higher than the speed on the curved path. This indicates that the walking speed is dropped at the corner and regained after the corner. Further, it can be observed that higher the turning angle, lower the speed on the curved path. In order to quantify this effect more precisely, the percentage speed reductions on curved paths (with respect to the approaching speed) were compared as shown in Table 3 and Table 4. Paired t-test was conducted to statistically compare the means of approaching speed and the speed on the curved path. Respective p values are also depicted in Table 3 and Table 4.

Table 3: Percentage reduction of speed and results of paired t-test for normal speed walking cases

	0°	45°	60°	90°	135°	180°
Percentage reduction relative to the approaching speed	-	2%	3%	9%	19%	32%
t test p value	-	p = 0.780	p = 0.645	p = 0.057	p << 0.01*	p << 0.01*

* p < 0.05: mean speeds are statistically significant at the 95% confidence level

Table 4: Percentage reduction of speed and results of paired t-test for fast speed walking cases

	0°	45°	60°	90°	135°	180°
Percentage reduction relative to the approaching speed	-	5%	7%	13%	30%	43%
t test p value	-	p = 0.085	p = 0.012*	p = 0.007*	p << 0.01*	p << 0.01*

* p < 0.05: mean speeds are statistically significant at the 95% confidence level

According to Table 3 and Table 4, it can be stated that the turning angles of more than 90° can significantly decrease the walking speeds when an individual walks on angled paths under normal walking conditions. This angle threshold can become low (i.e. up to 60°) when the desired speed is higher and that indicates that the effect of turning angle is magnified when individuals are in a rush (when their desired speeds are higher).

Furthermore, it can be argued that when the degrees of freedom increases (i.e. when the effect of walls and interpersonal interactions come in to play), the combined effect of these factors with turning angle can further reduce the collective walking speed. As mentioned in (Illera et al. 2010,) running towards a corner of a corridor with a higher turning angle (for example 90°) would be perceived as running straight into a wall and that uncertainty and hesitation can reduce the speed remarkably. Consequences of these combined effects are crucial under panic conditions when people try to escape as fast as possible and pushing and competing behaviours could also frequently occur.

5. Conclusions and Further Studies

Under this study, a series of experiments were designed and conducted in order to comprehensively understand the effect of turning angles on human walking speed under various conditions. Initial results obtained from analysing solo walking data suggest that turning angles of 90° or more are inefficient in terms of significantly reducing (approximately more than 9%) the walking speeds under normal conditions. This angle threshold can be reduced (for example up to 60°) when pedestrians' desired walking speeds are higher as verified with data collected from pedestrians walking at higher speeds.

Data and initial findings from this experimental research provide valuable insights into the understanding of microscopic walking characteristics in complex situations such as turning movements. Further, these data can be utilised to upgrade and enhance the microscopic pedestrian simulation models (to calibrate parameters and behavioural rules) to more realistically reproduce human walking behaviours related with common movements such as turning manoeuvres. With properly calibrated and verified simulation tools, it is possible to develop strategies which can accurately consider circuitous egress routes of mass gathering places in the design of the environment to enhance the safety of pedestrian crowds during emergency situations.

In the future, more degrees of freedom will be added to the experiments, for example the effect of walls (to incorporate the effect of blocked vision), bi-directional flows, high crowd density and so on, in order to more comprehensively quantify the combined effects of turning angle and other parameters. Further, the findings from these experimental studies will be verified with real world observations.

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