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Automated analysis of pedestrian walking behaviour at a signalised intersection in China

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Abstract: An analysis of pedestrian walking behavior using gait parameters is presented; it uses automated video analysis to collect pedestrian data at a signalized intersection in Nanjing, China. Two aspects of microscopic pedestrian behavior are considered: First, the walking mechanism represented by pedestrian gait parameters. Second, the non-conforming crossing behavior of pedestrians. The effect of various pedestrian related attributes are investigated. The results show high accuracy in automatically detecting pedestrian violations, with an 85.2% correct detection rate. The walking speed and gait parameters for spatial violators are found to be significantly higher compared to non-violators. It is also found that pedestrians who enter the crosswalk during the late stage of the green pedestrian phase often adopt higher walking speed. The gait analysis shows that males tend to have a higher walking speed, walk ratio and longer step length than females. Single pedestrians are found to have higher speed and step frequency compared to pedestrians in groups. The presence of bikes on crosswalks significantly decreases the pedestrian walking speed, step length and frequency, leading to more gait variability. Such results are useful for many future applications such as calibration of simulation models and violation detection.

1 Introduction

There is an increasing interest in promoting sustainable modes of transportation such as walking and cycling. Walking is identified as a leading driver for a healthy, liveable and resource-efficient environment [1]. As well, walking has a significant effect on reducing traffic congestion, energy consumption, and air pollution. However, while non-motorised modes of travel are presented as alternatives to motor vehicles for improving the sustainability of the transportation system, they suffer from an elevated risk of collision involvement [2]. Collisions involving pedestrians usually involve injuries and physical damage. In the developing world, the high vulnerability of pedestrians and the less attention given to non-motorised modes of transportation by policymakers, make the situation more dangerous. In a review of studies from developing countries, the frequency of pedestrian fatalities was ranked as the highest among all travel modes; accounting for 41 to 75% of all fatalities [3]. The problem of pedestrian accidents in developing countries is usually compounded by the higher population density, rapid rate of modernisation, and lack of compliance of traffic regulations by both drivers and pedestrians [4].

As communities become more aware of the benefits associated with active non-motorised modes of travel, pedestrian walking behaviour research is receiving a growing attention from policy makers and researchers [1]. Therefore, an in-depth understanding of walking behaviour is central to the evaluation of measures of walking conditions such as safety, comfortability and efficiency. This study investigates two aspects of microscopic pedestrian behaviour: walking mechanism as represented by the gait parameters and the non-conforming (violation) behaviour of pedestrians. Gait analysis is a microscopic-level analysis which allows the estimation of walking mechanism parameters such as step frequency and length for different pedestrian groups. Several applications are associated with gait analysis such as estimating the impact of shifting auto travel for active transportation modes such as walking [5]. Gait analysis is also useful in estimating the walking costs to different groups of pedestrians such as the elderly [1]. This allows the consideration of constraints on the movement ability of some pedestrians. Other direct applications are the classification of pedestrian attributes [6, 7] and the calibration of pedestrian micro-simulation models [8]. Traffic violations occur when road users such as pedestrians violate traffic regulations to seek increased mobility. This behaviour can result in increased collision risk. Therefore, the identification and understanding of non-conforming behaviour (violations) can be useful in the diagnoses of safety issues and the development of safety treatments. It can be useful to observe violations as surrogates for traffic conflicts and road collisions when the observation time is limited [9].

The goal of this paper is to improve the understanding of pedestrian walking behaviour in urban intersections in China through the automated analysis of video data. The effect of various attributes related to gender, group size, mixed traffic flow, and pedestrian signal control are investigated. In addition, pedestrian non-conforming behaviour is automatically detected and analysed. Video data from a busy intersection in Nanjing, China is used for the analysis.

2 Previous works

2.1 Pedestrian walking behaviour in China

Non-conforming pedestrian crossing behaviour is common in China where many pedestrians tend to ignore traffic rules, especially at signalised intersections. A study by Tanaboriboon and Jing [10] showed that illegal crossing behaviour at signalised crossings by pedestrians in Beijing account for 30 to 40%. Ren *et al.* [11] also found that the average pedestrian compliance rate is only 62.8% at signalised crosswalks in Nanjing. Several studies have identified several factors that affect pedestrian crossing behaviour, such as the physical environment, pedestrian attributes, and social factors [4, 11, 12]. Yang *et al.* [13] showed that pedestrians wait for an acceptable gap in traffic rather than a green signal in most cases at signalised intersection in the city of Xi'an. Guo *et al.* [14] reported that older pedestrians could tolerate a longer waiting time than younger ones which makes them more likely to comply with traffic rules. However, many pedestrians do not respect traffic signal rules in China compared with the developed world [13].

2.2 Gait analysis and measures

Gait analysis is emerging as one of the principal tools to study the walking behaviour of pedestrians. Key observations were identified during studying the effect of pedestrian characteristics and the traffic environment on the walking gait parameters such as gait length and gait frequency [15–24].

Distinct gait patterns were identified across gender and age. Females have shorter stride length and higher stride frequency compared with males [15, 16]. Older pedestrians were reported to have shorter stride length compared with younger ones [16, 17, 18, 25]. However, mixed results were reported on the relationship between age and step frequency [18, 19]. Some studies also investigated the variation of gait parameters across certain populations. Parameters such as the walk ratio (WR) was suggested to measure consistency in the walking pattern. Studies have shown that the WR in older pedestrians was smaller than that of young pedestrians, and tended to decrease with age [26]. Barrett *et al.* [27] and Hollman *et al.* [28] found that females have lower WR than males in healthy young subjects.

Early studies also investigated the impact of the walking environment on gait parameters. Kawamura *et al.*, [23] for example, showed that downgrades have significant effect on decreasing step length, but increasing step frequency, and upgrades have significant effect on increasing step length.

2.3 Pedestrian walking speed

In addition to the main gait parameters, the average walking speed is considered an important parameter to evaluate pedestrian behaviour. Pedestrian attributes, environment factors such as density, signalling scheme and facility configuration were shown to affect the walking speed. For example, Goh *et al.* [29] reported that pedestrians at non-signalised crosswalks had higher crossing speed than those at signalised crosswalks. The study in [12] showed that pedestrian crossing speed at countdown signals crosswalks are significantly higher than those at flashing crosswalks, especially at the end of the clearance time. Knoblauch *et al.* [30] found that pedestrians tend to have higher crossing speed on wider streets. In addition, the study showed that pedestrians who cross the intersection at flashing do not work phase have significant higher walking speed than those who start during the walk phase. In a study in Oakland California, Hediyeh *et al.* [31] evaluated the pedestrian crossing speed before and after the implementation of a scramble pedestrian phase. The average speed in the scramble phase was significantly larger than the average speed in pre-scramble phase when crossings through all, conventional, or diagonal legs of the scramble. It was also shown that the diagonally crossing pedestrians have significantly higher crossing speed than the conventionally crossing pedestrians in the scramble phase. Pedestrians who started crossing the intersection during ‘Walk’ indication walked slower than those who started crossing during ‘Flash Do not Walk’ indication. In addition, pedestrians had faster walking speeds through the first half of the crosswalk and slowed down as they approached the end of the crosswalk. Pedestrians attributes such as gender, age and group size were also found to affect pedestrian walking speed [29, 31–33]. It was also shown that the average pedestrian crossing speed decreased as the group size increases in both pre-scramble and scramble phases.

2.4 Pedestrian violations

The effect of both pedestrian attributes and environmental factors on pedestrian non-conforming (violation) behaviour has been the topic of several studies [14, 11, 34–37]. Demographic characteristics like gender and age have been found to affect pedestrian violations. Generally, males tend to violate traffic rules more frequently than females and are more likely to cross in risky situations. However, Ren *et al.* [11] found a contradictory result in China that male pedestrians are more likely to comply with traffic regulations compared with females, especially to those who are middle aged. The pedestrian group size also plays an important role in pedestrian temporal violations. It is reported that the higher the number of pedestrians waiting to cross together lead to lower rate of red light violation [36, 38].

The external environment factors were also found to affect the pedestrian violations. Sisiopiku *et al.* [37] investigated pedestrian behaviour at various crosswalk types. They found that unsignalised midblock crosswalks were the treatment of preference to pedestrians and also showed high crossing compliance rate of pedestrians. A recent study by Ma *et al.* [12] reported that a countdown pedestrian signal has a significant impact on increasing the compliance of older pedestrians. Karkee *et al.* [39] suggested a relationship between pedestrian crossing conformance and traffic conflicts. Other studies demonstrated that the waiting time, crossing time, length of crossings, and lane used also have impacts on pedestrian violations [32, 40].

2.5 Video-based automated computer vision pedestrian data collection

Traditionally, pedestrian data are collected using manual measurements by field observations. However, this manual method is labour-intensive, unreliable, time consuming, and costly. Video sensors are now advocated as an alternative data collection procedure, solving many issues in the manual data collection and providing a more practical and efficient way to capture, store, and analyse traffic information [6, 41]. Computer vision systems are developed to automatically detect and track moving objects in videos, providing an automated pedestrian data collection method. Automated computer vision techniques were successfully used in various pedestrian data collection such as pedestrian counts [33, 42], speed [31, 43], and violation [9, 44]. Recently, the automated techniques are adopted to extract pedestrian gait parameters from videos sensors. For example, Hediyeh *et al.* [1, 45] conducted studies that relied on computer vision techniques to collect pedestrian gait parameters and walking speed from Vancouver, British Columbia and Oakland, California. Gait variation parameters were useful for the automated classification of pedestrian attributes (e.g. gender and age) as demonstrated in [7, 46].

3 Study location

Video data are collected from a busy four-leg signalised intersection in Nanjing, China. The selected signalised intersection is located on North Taiping Road with Zhujiang Road (see Fig. 1). North Taiping Road is a north-south major corridor while Zhujiang Road serves as a commercial and business west-east corridor of Nanjing city. Pedestrian signals are installed at the intersection. A computer supermarket is located near the intersection, contributing to high pedestrian activity. The study location is perceived to have safety issues related to a high pedestrian violation rate. As shown in Fig. 1, the study focused on the north crosswalk (crosswalk 1) and the east crosswalk (crosswalk 2). The cycle length of pedestrian signals at the north and east crosswalks is 135 s. The green time of pedestrian signals are 40 and 55 s respectively. The signal timing and geometry information for the selected intersection are provided in Table 1. Video recording of the location was done for 5.5 h November 2010. The camera was placed on top of a roadside building to achieve good viewing height. Field data collection was conducted during weekday afternoon peak periods under fine weather conditions.

4 Methodology

The following section describes the methodology used to analyse walking behaviour and pedestrian violation. The computer video analysis system used in the study was developed at the University of British Columbia [41, 47], which includes two modules as shown in Fig. 2. The system can automatically detect road users, extract their trajectories, and identify pedestrian violation form a video scene. The system has been used in many safety analysis and data collection studies.

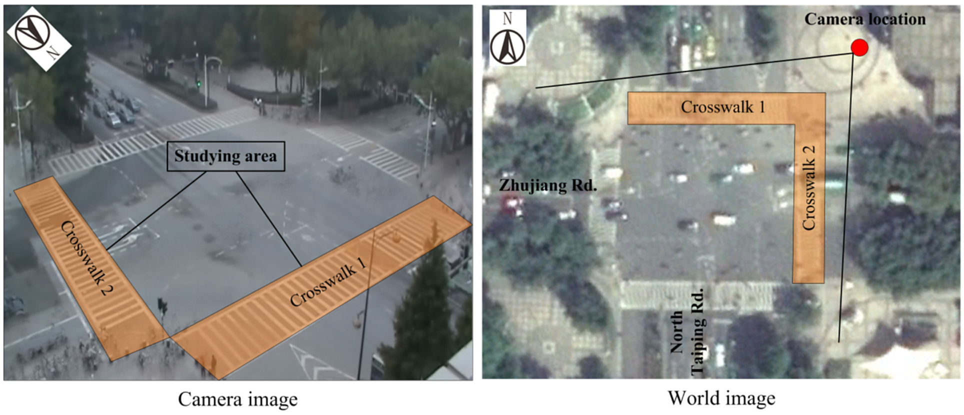

Fig. 1 *Data collection site and studying area*

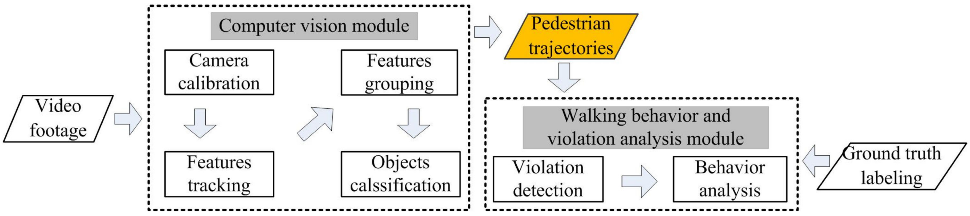

Fig. 2 *Video analysis block diagram*

4.1 Pedestrian trajectories extraction

The first task in the video analysis procedure is the process of camera calibration. The purpose of this calibration is to create a transformation that permits the recovery of real world coordinates (e.g. metric coordinates) from the pixel based coordinates of the video images. Such mapping between the real world and the image space lead to the correct collection of the tracked trajectory information such as positions and velocities of road-users such as pedestrians. Details and validation of the mixed-feature camera calibration approach can be found in Ismail *et al.* [48].

Following the camera calibration is the process of features tracking. Features on moving objects are identified and tracked using an implementation of Kanade–Lucas–Tomasi feature tracker algorithm [47]. In the current implementation, a filtering mechanism based on background subtraction is performed to differentiate between two types of stationary features. The first set of features that belong to the environment. Such features are discarded and not tracked. The second set of stationary features are those initially identified on moving road-users but were stationary for a period of time (e.g. a walking pedestrian stopping at a curb). Those features are considered valid features and are not discarded.

Features that are spatially close and move close to each other at similar speed and similar movement patterns are subsequently grouped together to create one road-user object. Those objects are then classified into different road users (e.g. vehicles, trucks, bicycles, pedestrians) depending on obvious indicators such as movement patterns, maximum speed, and road user size [6]. The tracking accuracy for this approach has been tested and found to be about 90%, which is considered reliable [44]. Only pedestrian trajectories are kept for further analysis in this study. The pedestrians' trajectories extraction procedure is shown in Fig. 3.

Table 1 Signal timing and geometric design of the selected intersection

	Southbound	Westbound
crosswalk length, m	30.7	38.7
crosswalk width, m	4.5	4.5
no. of lane[a]	6	7
pedestrian signal cycle length/green time, s	135/55	135/40
separated bike lane	yes	yes
parking/bus stop operation	no	no

[a]Both directions.

4.2 Pedestrian walking speed and gait parameters analysis

The outcome of the video analysis performed on the data is a set of trajectories representing the temporal evolution of the pedestrians' movement. The walking speed and acceleration behaviour are directly derived from those trajectories in the form of time series profiles. Speed variations which are the result of the pedestrian taking a step forward are expressed though cyclic fluctuations in the speed profile. The number of times a foot touches the ground in a unit of time is then designate the step frequency. As such, step frequency could be estimated from the reciprocal of cycles [7]. This estimation is simply performed by evaluating the power spectral density (PSD) of the speed profile [1] and selecting the dominant frequency component (periodicity) in the speed profile. This is realised by calculating the periodogram of the speed profile signal (i.e. mean square of the discrete Fourier transform of the signal).

The PSD estimate for each frequency f is given by

$$P(f) = \frac{1}{F_s\, n} \left| \sum_{i=1}^{n} s_i e^{-(-\mathrm{j}(2\pi f) i / F_s)} \right|^2 \tag{1}$$

where F_s is the sampling frequency; k is the number of video frames.

Once the step frequency and walking speed of a pedestrian are determined, the average step length can be calculated from the fundamental linear relationship

$$S_{\text{wlk}} = F_{\text{stp}} \times L_{\text{stp}} \tag{2}$$

where S_{wlk} represents pedestrian walking speed; F_{stp} represets step frequency; and L_{stp} represents step length. Pedestrian walking speed is estimated directly from pedestrian speed profile as the average speed through the entire crossing time.

4.3 Gait variation

For the pedestrian behaviour analysis in this study, the gait parameters are complimented with three additional parameters to measure pedestrian gait variation.

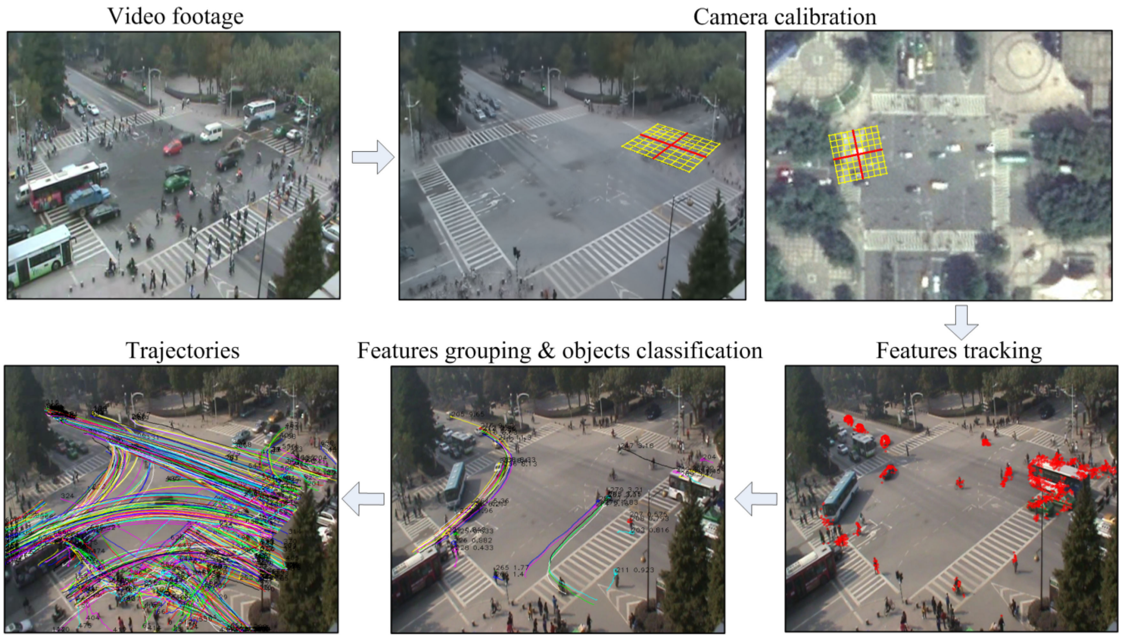

Fig. 3 *Pedestrians trajectories extraction procedure*

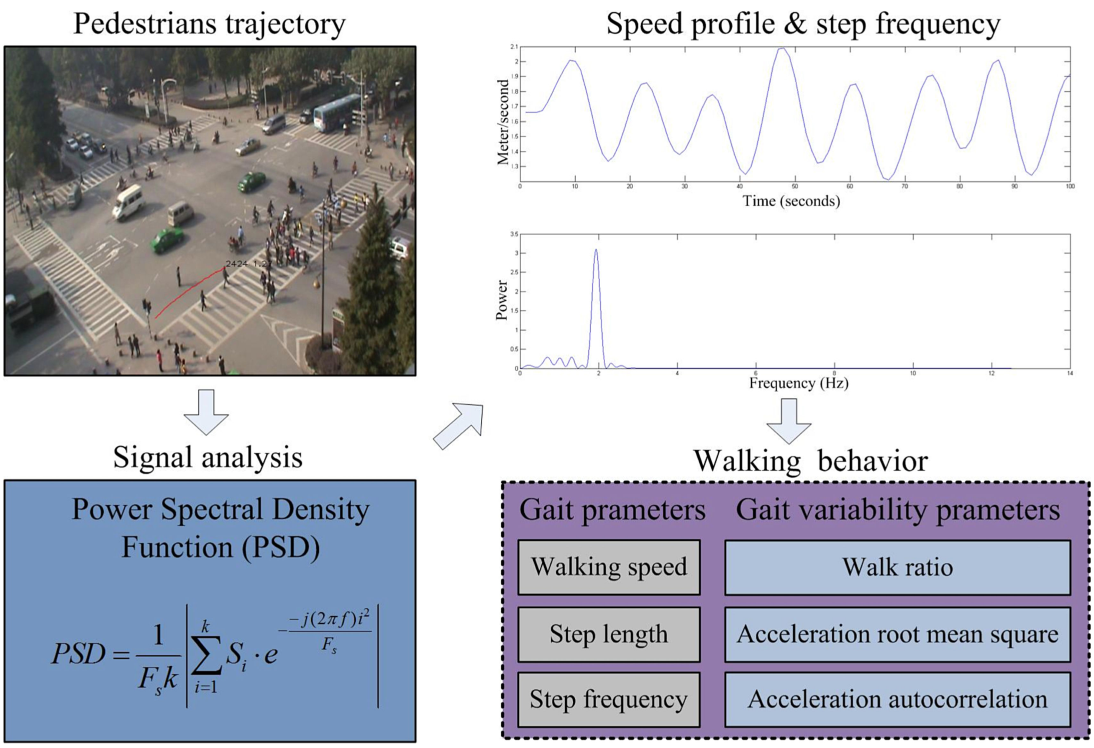

Fig. 4 *Pedestrian walking speed and gait parameters extraction procedure*

4.3.1 Walk ratio: The WR is a speed independent index to describe the walking pattern (i.e. temporal and spatial coordination during walking). It is calculated as the average step length divided by step frequency [46, 49]:

$$\mathrm{WR} = \frac{L_{\mathrm{stp}}}{F_{\mathrm{stp}}} \tag{3}$$

It is important to note that in theory, at any given speed, a pedestrian can walk with infinite combinations of step length and step frequency. However, as previous study showed [49], subjects do not tend to vary their speed ratio over wide ranges of speed. Deviations from the normal WR during free walking may then reveal a degree of abnormality in the walking pattern.

4.3.2 Acceleration root mean square (RMS): The acceleration RMS is a measure of dispersion of the pedestrian normalised acceleration profile. This parameter provides a measure of the average magnitude of accelerations as the pedestrian walk across a specified segment. A higher RMS indicates a higher degree of variability and a lower degree of stability [46].

4.3.3 Acceleration autocorrelation (AAC): The AAC is a measure of the pedestrian step similarity and regularity. This is performed by examining the similarity of the acceleration profile shape. A higher AAC value designates a greater degree of gait stability. AAC is estimated using Pearson's correlation coefficient with lag time defined as a function of an arbitrary number of steps [50].

The pedestrian walking speed and gait parameters extraction procedure is shown in Fig. 4.

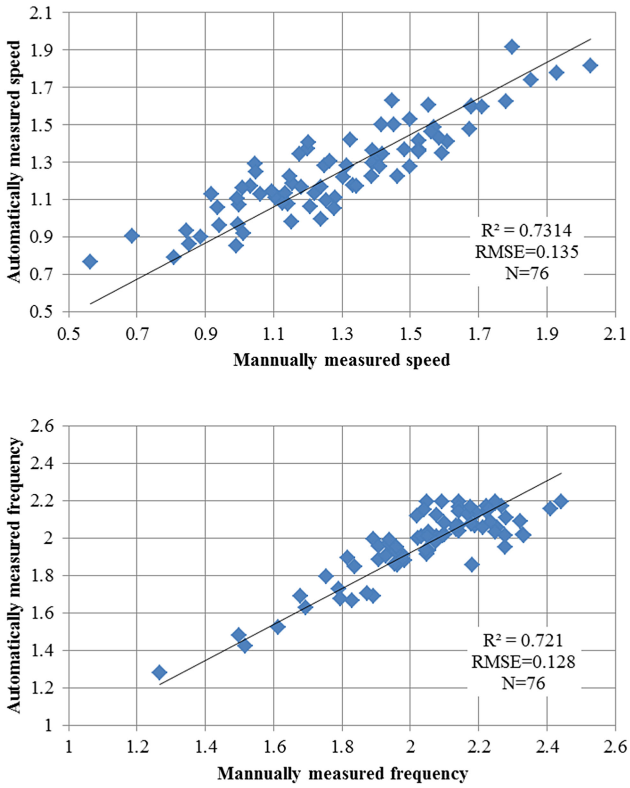

Fig. 5 *Validation of walking speed and step frequency*

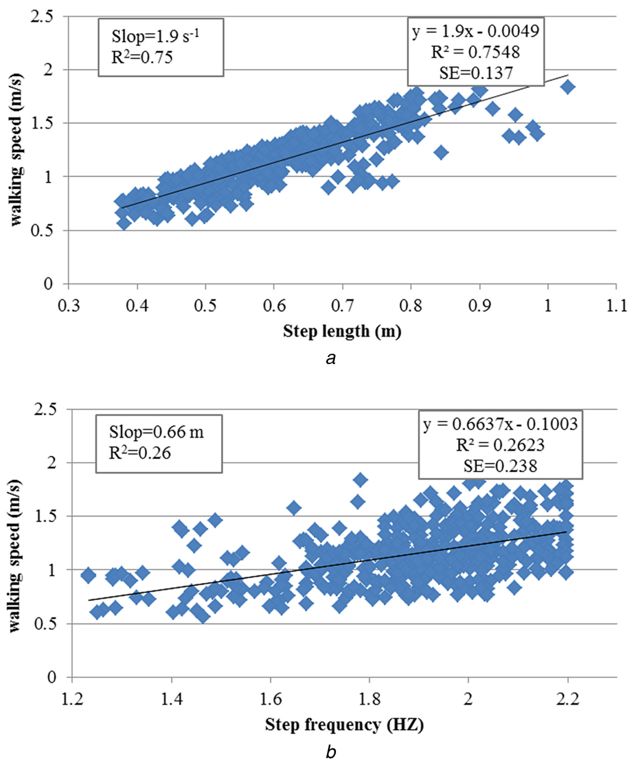

Fig. 6 *Relationship between walking speed and gait parameters*
(a) Relationship between walking speed and step length, ***(b)*** Relationship between walking speed and step frequency

4.4 Pedestrian spatial violation detection

Automated spatial violations detection starts with generating a set of movement prototypes. After extracting the trajectories of pedestrians from the video scene, the movement prototypes, which refer to a group of motion patterns that define the set of movements, for normal (e.g. conforming) crossing pedestrians are selected. Subsequently, a comparison is performed between a pedestrian trajectory and the set of movement prototypes. The comparison task is set up as a similarity measure. The longest common sub-sequence (LCSS) algorithm is adopted to identify how close the behaviour of a walking pedestrian to that of the 'normal' behaviour represented by the movement prototypes. A lower similarity is then interpreted as evidence that the given trajectory represents the movement of a violation pedestrian. Such procedure leads consequently to the identification of violating pedestrians. Details of the LCSS algorithm can be found in [9, 51].

5 Summary of results

5.1 Walking speed and step frequency validation

The automatically extracted values of walking speed and step frequency are validated by comparing them with the manually calculated values. 76 pedestrians are randomly selected for the validation. The root-mean-square error is calculated. Results in Fig. 5 show reasonable accuracy of the automated system for measuring the walking speed and the step frequency.

5.2 Relationship between walking speed and gait parameters

The relationship between pedestrian walking speed and gait parameters is examined in this study. The Pearson correlation coefficient between walking speed and step frequency, and step length are estimated. The results show that the correlation between walking speed and step frequency (correlation coefficient = 0.512, p-value = 0.00), and between walking speed and step length (coefficient = 0.869, p-value = 0.00) are found to be statistically significant. Furthermore, a simple liner regression is used to quantify the relationship. As shown in Fig. 6, a linear correlation provides good fit for the relationship between walking speed and step length but not the step frequency. As shown in the figures, one unit change in the step length leads to 1.9 unit change in the walking speed, while one unit change in the step frequency leads to 0.66 unit change in the walking speed, indicating that the effect of step length on walking speed is more significant than the effect of step frequency on walking speed. This result is confirmed by the previous studies by Hediyeh *et al.* [45] and Reyad *et al.* [52]. Some other studies [53] also reported that the relationships between stride length, step frequency and walking speed vary by age in the form of a linear equation or log–log linear equation.

5.3 Pedestrian spatial violation

Due to the high density and high volume of pedestrians at the two crosswalks, 662 high quality pedestrian trajectories are selected for analysis. Figs. 7*a* and *b* show the trajectories for normal (non-violating) and spatial-violation pedestrians, respectively. Fig. 7*c* shows the synthetic pedestrian prototypes used in the LCSS-based violation detection. For validation purposes, pedestrians in the scene were manually identified and classified to be used as ground truth. The confusion matrix in Table 2 shows the performance of the automated violation detection process.

At a false detection rate of 12.1% (non-violating pedestrian identified as violating), a correct detection rate of 85.2% (true violators) can be achieved. The results indicate a reasonable accuracy of the automated detection of spatial violations. As shown in Fig. 7*b*, a high level of pedestrian crossing violations was detected at crosswalk 1 boundaries, especially at the chevron road marking area as shown in Fig. 8. Field observations made it clear that the chevron road markings that separated the motorised lanes and bicycle lane contributed to the spatial violations. When pedestrians intend to reach the downstream area of North Taiping road, they cross the chevron road marking area as a shortcut, resulting in numerous spatial violations. Fig. 9 shows sample pedestrian violations.

6 Discussion

6.1 Effect of different attributes on walking speed and gait parameters

The effects of several attributes on walking speed and gait parameters are investigated below. Table 3 shows a comparison of

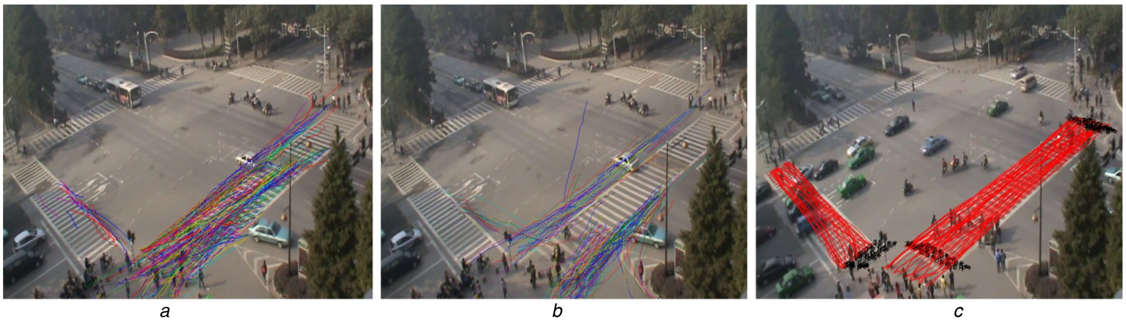

Fig. 7 *Pedestrian tracks extracted from the video data*
(a) Non-violating, ***(b)*** Spatial violating, ***(c)*** Movement prototypes

Fig. 8 *Pedestrian spatial violation illustrations*

Fig. 9 *Sample pedestrian violations*
(a) Diagonal crossing, ***(b)*** Violation crosswalk, ***(c)*** Violation at chevron road markings, ***(d)*** Violation at chevron road markings

Table 2 Performance of the violation detection

	Automatic	
manual	normal	violator
normal	333	46
violator	42	241

gait parameters and walking speed for different pedestrian characteristics.

6.1.1 Gender: Walking speed and step length are found to be significantly different between males and females. Compared with females, males tend to have significant higher speed, longer step length and higher WR. However, step frequency of male pedestrians is not statistically different than females. This may suggest that male pedestrians increase their walking speed by increasing their step lengths rather than step frequency [54, 55]. The finding is consistent with results reported in other studies [45, 56, 57]. Males have slight higher acceleration RMS and lower AAC than females. However, the differences of these two parameters between males and females are not found to be statistically significant in this study.

6.1.2 Group size: The walking speed and step frequency are mainly influenced by size of the pedestrian group. Walking speed and step frequency for pedestrians walking alone are significantly higher than those who walk in groups. The step length of pedestrians walking alone is also found to be higher than that in groups; however, the difference is not statically significant. The finding may be due to that available space is limited for a pedestrian in groups to change step length. Therefore, pedestrians in group manage to adjust their walking speed by changing their step frequency to accommodate slower companions. The finding is supported by several previous studies [52, 56]. In addition, the significantly higher acceleration RMS and lower AAC for pedestrians in groups indicate that they tend to have more variability in walking compared with single pedestrians.

6.1.3 Bikes on the crosswalk [Here bikes refer to motorcycles, e-bikes and bicycles]: Bikes were frequently observed traveling on the crosswalk with pedestrians, especially during the early part of green pedestrian signal. This has a significant impact on walking speed and gait parameters as well as gait variation parameters. The walking speed is significantly lower when there are bikes travelling with pedestrians compared with when there is no bikes present on the crosswalk. The step length and step frequency are also found to be significantly different when bikes are present. Pedestrians have more gait variability when bikes are present on the crosswalk as demonstrated by the statistical significance of the difference in WR, the acceleration RMS and the AAC.

6.1.4 Spatial violation: As mentioned earlier, pedestrian spatial violations were automatically identified. The walking speed and gait parameters for violators were found to be higher than those of non-violators. Violators tend to have significant higher walking speed compared with non-violators. The difference in walking speed is represented by an increase in both the step frequency and step length. This may be attributed to violators often having higher speed to complete crossing quickly to avoid higher crash risk. As well, an interesting finding is that the acceleration RMS is slightly but significantly higher for non-violators, which shows that non-violators tend to have higher degree of variability and less degree of stability compared with violators. The significantly lower AAC for non-violators also confirm higher gait variability. The results provide insight into the walking mechanism of pedestrians involved in spatial violations when crossing signalised intersections.

6.1.5 Green pedestrian signals: To better understand the influence of pedestrian signals on walking behaviour, the green pedestrian cycle length is divided into three equal periods (termed stage 1, stage 2, and stage 3). Pedestrians who enter the crosswalk during the late stage (stage 3) have significantly higher walking speed, step frequency and longer step length compared with pedestrians entering the crosswalk in the first two stages. This indicates that pedestrians adopt higher speed when they are crossing during the late stage of the green pedestrian signals to avoid being in temporal violation.

6.2 Comparison with results from other countries

A comparison between the results of this study and results from other cities is conducted. Results from Vancouver [1], New York [56], Oakland [45] and Doha [52] are used in the comparison as shown in Fig. 10. An analysis of variance was conducted to identify whether the difference of gait parameters among different cities is statistically significant. In general, it was found that the walking speed and step length in China were significantly lower than those from western countries for both males and females. However, the pedestrian step frequency is not statistically different between the studies in China and western countries. Although, some conclusions can be made from this comparison, it is important to have a more thorough analysis and larger data sets before drawing any significant conclusions about the findings.

7 Summary and conclusions

This study focused on data from a busy urban intersection in China. Five and a half hours of video data was collected at a busy signalised intersection in Nanjing during the peak period. Walking mechanism represented by gait parameters and non-conforming behaviour of violating pedestrians were analysed by means of video-based computer vision techniques.

Table 3 Comparison of gait parameters and walking speed across different characteristics

Attribute	Variable	Count	Step frequency, Hz	Walking speed, m/s	Step length, m	Walk ratio, m/Hz	Acceleration RMS	Acceleration autocorrelation
gender	male	333	1.888 [0.214]	1.170 [0.276]	0.620 [0.127]	0.666 [0.166]	0.326 [0.147]	0.195 [0.150]
	female	119	1.899 [0.216] (0.313)	1.111 [0.280] (0.024)[c]	0.584 [0.124] (0.004)[c]	0.623 [0.156] (0.005)[c]	0.310 [0.167] (0.168)	0.209 [0.164] (0.200)
group size	single	278	1.940 [0.191]	1.188 [0.288]	0.613 [0.138]	0.639 [0.169]	0.306 [0.143]	0.199 [0.147]
	2+	174	1.812 [0.225] (<0.001)[c]	1.101 [0.251] (<0.001)[c]	0.606 [0.108] (0.281)	0.679 [0.155] (0.005)[c]	0.346 [0.164] (0.004)[c]	0.198 [0.164] (0.463)
bikes on crosswalk	yes	98	1.789 [0.241]	0.921 [0.155]	0.520 [0.090]	0.599 [0.171]	0.385 [0.151]	0.176 [0.140]
	no	354	1.919 [0.197] (<0.001)[c]	1.219 [0.269] (<0.001)[c]	0.635 [0.124] (<0.001)[c]	0.670 [0.160] (<0.001)[c]	0.304 [0.149] (<0.001)[c]	0.205 [0.157] (0.043)[c]
spatial violation	yes	190	1.916 [0.216]	1.201 [0.265]	0.626 [0.117]	0.662 [0.151]	0.305 [0.148]	0.213 [0.150]
	no	262	1.872 [0.211] (0.014)[c]	1.121 [0.282] (0.001)[c]	0.599 [0.132] (0.011)[c]	0.650 [0.174] (0.216)	0.334 [0.155] (0.023)[c]	0.188 [0.155] (0.039)[c]
green pedestrian signals	stage 1	211	1.882 [0.215]	1.156 [0.281]	0.613 [0.123]	0.659 [0.156]	0.317 [0.154]	0.196 [0.149]
	stage 2	140	1.870 [0.222] (0.303)	1.091 [0.252] (0.017)[c]	0.586 [0.128] (0.027)[c]	0.640 [0.184] (0.159)	0.333 [0.142] (0.157)	0.206 [0.165] (0.282)
	stage 3	101	1.938 [0.194] (0.006)[c]	1.240 [0.284] (<0.001)[c]	0.639 [0.128] (<0.001)[c]	0.666 [0.154] (0.118)	0.317 [0.165] (0.212)	0.192 [0.148] (0.244)

[a]Represents the standard deviation.

[b]Represents the *p*-value of *t*-test or ANOVA-test.

[c]Indicates statistically significant difference (at 95% confidence level) compared with the cell directly above.

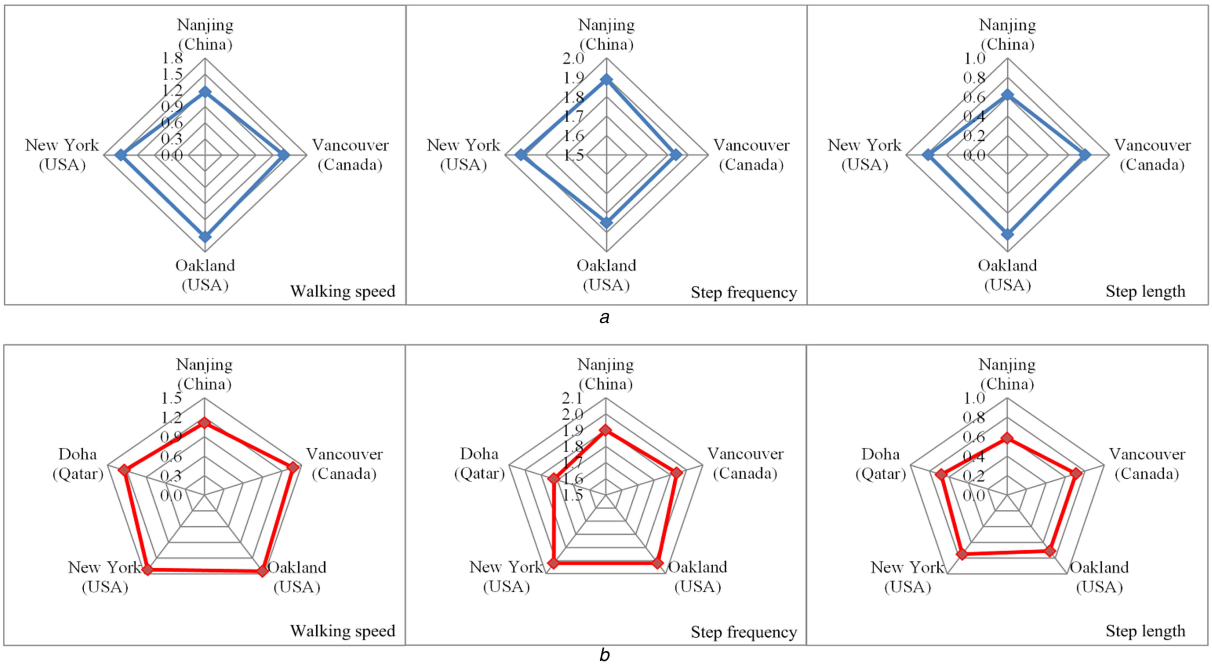

Fig. 10 *Comparisons of gait parameters across gender*
(a) Comparison of gait parameters for male, ***(b)*** Comparison of gait parameters for female

In this study, pedestrian spatial violation was automatically detected from the video scene. The results show a satisfactory accuracy in the detection of spatial violations, with an approximately 85.2% correct violation detection rate. The results show a high level of pedestrian crossing violations occurring near the crosswalk boundaries. It also reveals that an existing chevron road markings lead to a high number of spatial violations. As pedestrian violations contribute to the safety issues at the intersection, it is recommended to apply engineering countermeasures to decrease the number of violations to improve safety [58].

The gait parameters (walking speed, step length, and step frequency) and dynamic gait parameters (WR, acceleration RMS, and AAC) related to gait variation measures were automatically extracted for 452 pedestrians. The automatic values of walking speed and step frequency were then validated by comparing the automated and manually calculated values of 76 pedestrians and the results show a high accuracy of the automatic pedestrian data. Gait features were examined across different characteristics. The results show that various attributes related to gender, group size, mixed traffic flow, violation, and pedestrian signals control significantly affected walking speed, gait parameters and gait variability of pedestrians. The results also showed that the presence of bikes on crosswalks, pedestrian spatial violation, and different stages of pedestrian signals have significant effects on pedestrian walking speed.

Future research includes an expansion of the data used in this study to include different pedestrian facilities. One key task is to explore the use of automated conflicts analysis to examine the impact of traffic safety on the gait behaviour. Studying the relationship between pedestrian compliance to traffic regulations and factors such as waiting time, and intersection design characteristics should also be investigated to better understand violation behaviour. Finally, one long term research objectives is to explore the integration of such automated data collection in modern intelligent transportation systems applications. In particular, collision avoidance and safety monitoring applications can greatly benefit of the automatic identification of violators [59–61]. The results in this paper, can also be used during the calibration of pedestrian simulation models [62, 63]. Such research direction is currently under investigation at the UBC transportation research team, with promising early results indicate the benefits of using gait attributes in improving pedestrian modelling.

8 References

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