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Analysis of Pedestrian Fractures in Collisions Between Small Cars and Pedestrians Based on Surveillance Videos

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Objective: To discuss the collision relationship and the cause of the fracture caused by traffic accidents in which the front of a small car collides with the side of a pedestrian while braking.

Methods: The surveillance videos of 42 traffic accidents involving the front of a small car colliding with the side of a pedestrian while braking were collected. By analyzing the surveillance videos and the paths, the speed of the collision, the relationship between the vehicle and the pedestrian upon collision, and the movement trajectory of the human body were clearly identified. The type and severity of the injuries were also determined through autopsy. The characteristics of the human injuries and vehicle paths were analyzed according to the collision speed (<40 km/h, 40–60 km/h, 60–90 km/h), and the correlations between the fracture and the height of the pedestrian, the height of the hood and the length of the hood were discussed.

Results: When a small car hits the side of a pedestrian, the front bumper first hits the lower limbs of the pedestrian, and then, the human body falls to the side of the vehicle, causing a secondary collision with the hood and front windshield; thus, the pedestrian is thrown at a speed similar to the speed of the vehicle, finally falling to the ground and sliding forward a certain distance. (1) When V is less than 40 km/h (n = 10), the pedestrian's head did not collide with the windshield, and the fatal injuries were caused by the individual striking the ground. (2) When V is greater than 40 km/h (n = 32), the majority (97%) of cases showed collision with the windshield. (3) When 40 to 60 km/h (n = 16), the pedestrian's head collided with the windshield, which can cause fatal injuries, and pelvic fractures and rib fractures occurred in 56.25% of patients. (4) When V is less than 60 km/h (n = 26), the ratio of the height of the pedestrian to the height of the hood was significantly smaller in the pelvic fracture group than in the nonpelvic fracture group ($P < 0.01$). (5) When 60 to 90 km/h (n = 16), there were holes in the windshield, and the pedestrians experienced severe head injuries, with cervical spine fracture occurring in 37.5% of patients, pelvic fractures occurring in 43.75% of patients, and rib fractures occurring in 31.25% of patients.

Conclusions: When V is less than 40 km/h, the vehicle does not cause severe injuries in pedestrians; when V is greater than 40 km/h, the collisions of the pedestrian's head with the windshield lead to severe head injuries and the accident can cause severe pelvic and rib fractures; when V is greater than 60 km/h, the collisions of the pedestrian's head with the windshield can cause cervical spine fracture in addition to head injuries. The occurrence of human injuries is related to not only the vehicle speed but also factors such as the height of the pedestrian, the height of the hood and the length of the hood.

Key Words: forensic pathology, traffic injuries, surveillance video, collision speed, accident reconstruction

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At present, more than one million people die in road traffic accidents worldwide every year, approximately 50 million people become disabled, and the direct economic loss amounts to more than 500 billion US dollars.[1] These accidents obviously constitute a serious social problem,[1] especially in developing countries.

A collision between a small car and pedestrian is a relatively common type of accident among road traffic incidents. Research methods regarding road traffic incidents mainly include animal collision experiments, cadaver collision experiments, dummy collision experiments, software-based accident process restoration, and mathematical finite element models. Although animal collision experiments are valuable for studying the morphological characteristics and pathophysiological changes at some specific sites of injury, there are large differences in anatomical structure and organ tissue tolerance, so few animal collision experiments have been conducted. In the 20th century, some scholars used cadavers to study injuries.[2] However, cadavers lack the responsiveness of living muscle tissue, which makes it impossible to directly observe pathophysiological changes. Moreover, because of the limitations regarding ethics and regulations, cadaver collision experiments cannot be carried out. At present, dummy models that are similar to the human body in structure and physical characteristics are used in place of cadaver, and this method is relatively ideal for studying impact injuries at present. For example, in 2000, Bostrom et al[3] used a bionic dummy to determine the mechanism of neck injuries in rear-end collisions. However, dummy models are expensive and cannot reveal pathophysiological changes. In recent years, computer visual models have been widely used in automobile collision simulations.[4–10]

Currently, the models used in collision research on small cars and pedestrians mainly include multi-rigid-body models and finite element models. For example, Liu et al[11,12] used a finite element model to research injuries that occur in humans due to human-vehicle collisions, Han et al[13] used a multirigid-body model and finite element model to research head and chest injuries caused by car-pedestrian collisions, and Yao et al[14] recreated car-pedestrian collisions by using multirigid-body and finite element models. Although mathematical computer simulations can provide relatively accurate data for the study of collisions between

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small cars and pedestrians, computer models still have many limitations in forensic medical research because it is difficult to reconstruct complex anatomic geometry models and accurately recreate damage patterns.[15] For example, PC-Crash and MADYMO software have important practical value in the recreation of accidents and yield simulation results that are the most consistent with the actual results; however, the pedestrian model in this kind of software is simple in structure and lacks complex and diverse materials and properties, so it has many limitations in the evaluation of traffic injuries.[11,16,17]

Surveillance videos can theoretically capture the entire process of an accident, including the movement of the human body. With the vehicle paths and autopsy findings, the collision relationships between the vehicles and pedestrians, as well as the correlations between speed, paths and human injuries, can be clearly identified.[18] Although there are differences across monitoring devices and weather, distance and viewing angle influence the data, most of these factors can be accounted for by computers[19]; thus, the accident can be recreated, and the mechanisms of major traffic injuries can be revealed. Compared with other research methods, this method has many advantages.[19,20]

This study uses surveillance videos to explore the characteristics and the mechanisms of pedestrian injuries by determining the relationships between the vehicle and pedestrian, collision speed and human movement trajectories during actual traffic accidents in which the front of a small car collides with the side of a pedestrian.

MATERIALS AND METHODS

Materials

From 2015 to 2019, the surveillance videos of 42 fatal traffic accidents in which the front of a small car collides with the side of a pedestrian while braking were retrieved. The decedents were all between 20 and 50 years old. An accident site inspection, an accident vehicle inspection, surveillance video correction, and a systematic forensic pathological anatomy examination were conducted in all cases.

Methods

This study divided the collision speed into 3 ranges, <40 km/h, 40 to 60 km/h, and 60 to 90 km/h, based on the Road Traffic Safety Laws of the People's Republic of China, the Regulation and the Implementation of the Road Traffic Safety Laws of the People's Republic of China, and the general speed limits for urban, county, and provincial roads in China. The collision speeds of the cars were calculated by using the surveillance videos according to the national standards of the People's Republic of China (GB/T33195-2016, GA/T 1087-2013). Damage information, such as the damage to the front bumper, hood and front windshield, was retrieved from the accident inspection records for the vehicle, and the height of the front edge of the hood from the ground (hood's height) and the length of the hood (hood's length) were measured. The ratio of the height of the pedestrian to the height of the hood (pedestrian's height/hood's height) and the ratio of the pedestrian's height to the height of the hood plus the length of the hood (pedestrian's height/[hood's height + hood's length]) were calculated. Through the correction and analysis of the surveillance videos, as well as the evaluation of the trace inspection and autopsy records, the collision relationships between the small cars and pedestrians were identified, and the collision processes were verified and restored.[21] The autopsy report recorded the fractures and the damage of each organ in detail, and the damage degree of the human body was evaluated according to the injury severity score on the abbreviated injury scale (AIS).[22–24]

TABLE 1. Vehicle Damage, Human Body Injuries, and AIS Scores of the Injuries Caused by Collisions at Different Speeds

	Vehicle Damage			Human Body Injuries†(Case Percentage)						AIS Scores		
The Collision Speed: V*(No. Cases)	Front Bumper	Engine Cover	Front Windshield	Tibiofibular Fractures	Femoral Fractures	Pelvic Fractures	Fractures of the Rib	Cervical Spine Fractures	Head Injuries	Minor (≤16)	Serious (16–25)	Severe (>25)
<40 (10)	10	10	0	4 (40%)	1 (10%)	3 (30%)	3 (30%)	0	0	10	0	0
40–60 (16)	16	16	16	16 (100%)	5 (31.25%)	9 (56.25%)	9 (56.25%)	0	16 (100%)	0	9	7
60–90 (16)	16	16	15	15 (93.75%)	8 (50%)	7 (43.75%)	5 (31.25%)	6 (37.5%)	15 (93.75%)	0	4	12
Total (42)	42	42	32	35	14	19	17	6	41	10	13	19

*The unit of vehicle speed V is km/h, which is the same in the following table. †The human body injuries refer to direct collision injuries, not including fall injuries.

TABLE 2. The Correlation Between Damaged Front Windshield and Pedestrian Height/(Bonnet Height + Bonnet Length) in the 32 Cases With V > 40 km/h

The Collision Speed: V (32)	Front Windshield	
	Damaged (31)	Undamaged (1)
V > 40	0.96 ± 0.04	0.87

Moreover, whether there is a correlation between pedestrian fractures and pedestrian height/hood height and pedestrian height/(hood height + hood length) was explored.

RESULTS

Of the 42 accidents investigated, 10 had a collision speed <40 km/h, 16 had a speed between 40 and 60 km/h, and 16 between 60 and 90 km/h. Damage to the cars was mainly concentrated on the front bumper, hood, and front windshield. The data show that all the vehicles involved in the accident incurred damage to the front bumper and hood (100%), and the damage to the windshield was related to the vehicle speed, pedestrian height, hood height, and hood length.

(1) The Process of Collision

According to the analysis of the surveillance videos in this research, when a small car hits the side of a pedestrian, the front bumper first hits the lower limbs of the pedestrian, and then, the human body falls to the side of the vehicle, causing a secondary collision with the hood and front windshield; thus, the pedestrian is thrown at a speed similar to the speed of the vehicle, finally falling to the ground and sliding forward a certain distance.

(2) Front Windshield

When V is less than 40 km/h, the windshield was not damaged in any of the 10 cases; when 40 to 60 km/h, a spider-web-like damage pattern was found on the windshield in all 16 cases (100%); when 60 to 90 km/h, a hole in the windshield occurred in 15 of the 16 cases (93.75%). When V is greater than 40 km/h, the front windshield was damaged in 31 of 32 cases, mainly because of the collision of the pedestrian's head with the windshield; in these cases, the pedestrian height/(hood height + hood length) was 0.96 ± 0.04. In the remaining case, the windshield was not damaged, and the pedestrian height/(hood height + hood length) was 0.87 (Table 1, Table 2).

(3) Pedestrian Fracture

The injuries of the pedestrians mainly affected the tibia, fibula, femur, pelvis, ribs, cervical vertebra, and head. Tibiofibular fractures and head injuries were the most common, whereas fractures of the femur, pelvis, ribs, and cervical vertebrae also being common (Table 1, Fig. 1).

Tibiofibular fractures: a total of 4 of the 10 (40%) accidents with V less than 40 km/h involved tibiofibular fractures, whereas 31 of the 32 (96.87%) accidents with V greater than 40 km/h involved tibiofibular fractures. Only 1 accident with V greater than 40 km/h did not result in a tibiofibular fracture.

Femoral fractures: a total of 1 of 10 (10%) accidents with V less than 40 km/h involved femoral fractures; 5 of 16 (31.25%) accidents with V of 40 to 60 km/h involved femoral fractures; 8 of 16 (50%) accidents with V of 60 to 90 km/h involved femoral fractures. The probability of femoral fractures tended to gradually increase with increasing speed.

Pelvic fractures: a total of 3 of 10 (30%) accidents with V less than 40 km/h involved pelvic fractures; 9 of 16 (56.25%) accidents with V of 40 to 60 km/h involved pelvic fractures; and 7 of 16 (43.75%) accidents with V = in 60–90 km/h involved pelvic fractures. When V is less than 60 km/h, the probability of pelvic fractures tended to gradually increase with increasing speed; however, when V is greater than 60 km/h, the probability of pelvic fractures did not increase with increasing vehicle speed.

Fractures of the rib: a total of 3 of 10 (30%) accidents with V less than 40 km/h involved rib fractures; 9 of 16 (56.25%)

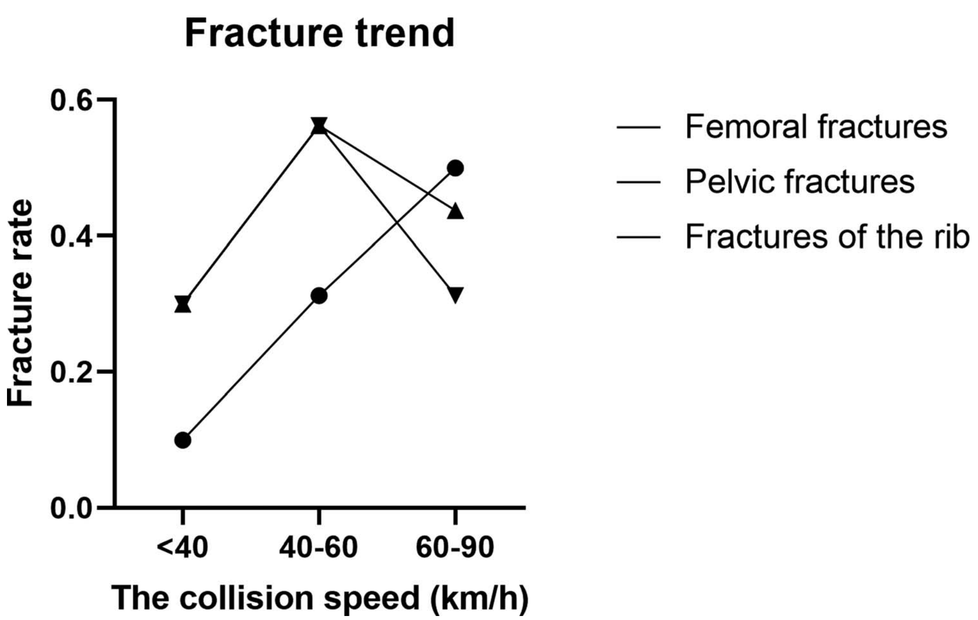

FIGURE 1. The probability of femoral fractures tended to gradually increase with increasing speed. When V < 60 km/h, the probability of pelvic and rib fractures tended to gradually increase with increasing speed; however, when V > 60 km/h, the probability of fracture did not increase with increasing vehicle speed.

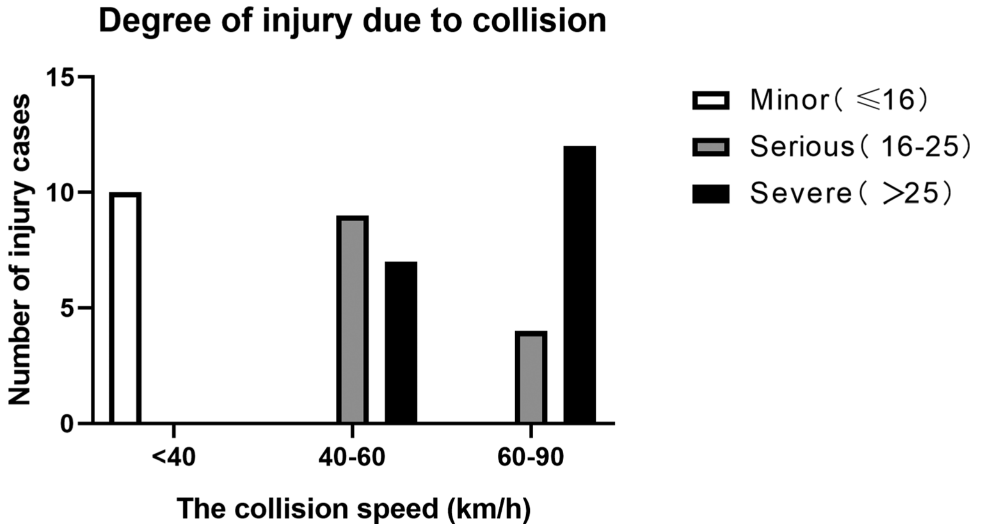

FIGURE 2. When V < 40 km/h, the AIS values were less than 16 in all 10 cases (minor injuries); when V = 40–60 km/h, there were 9 cases with AIS values ranging from 16–25 (serious injuries) and 7 cases with AIS values greater than 25 (severe injuries); when V = 60–90 km/h, there were 4 cases with AIS values ranging from 16–25 (serious injuries) and 12 cases with AIS values greater than 25 (severe injuries). The degree of pedestrian injury became increasingly severe with increasing vehicle speed.

accidents with V of 40 to 60 km/h involved rib fractures; and 5 of 16 (31.25%) accidents with V of 60 to 90 km/h involved rib fractures. When V is less than 60 km/h, the probability of rib fractures tended to gradually increase with increasing speed; however, when V is greater than 60 km/h, the probability of rib fractures did not increase with increasing vehicle speed.

Cervical spine fractures: when V is less than 60 km/h, no cervical spine injuries were found in any of the 26 cases; when V is greater than 60 km/h, cervical spine fracture were discovered in 6 of the 16 cases, 2 of which were accompanied by pelvic fractures, accounting for 12.5% of cases. A total of 10 cases did not involve cervical spine fracture, 5 of which involved pelvic fractures, accounting for 31.25% of cases.

(4) Degree of Injury Due to Collision

When V is less than 40 km/h, 2 cases had AIS scores less than 8 (minor injuries) and the remaining 8 all had AIS scores less than 16 (moderate injuries); when 40 to 60 km/h, there were 9 cases with AIS ranging from 16–25 (serious injuries) and 7 cases with AIS greater than 25 (severe injuries); when 60 to 90 km/h, there were 4 cases with AIS ranging from 16 to 25 (serious injuries) and 12 cases with AIS greater than 25 (severe injuries). The degree of pedestrian injury became increasingly severe with increasing vehicle speed (Table 1, Fig. 2).

(5) The Correlations Between the Pedestrian Injuries and the Height of the Pedestrian and the Height of the Hood

Considering the 42 cases in this study, the height of the pedestrian was 162 ± 6.59 cm, the height of the hood was 80.74 ± 3.77 cm, the length of the hood was 90 ± 5.2 cm, pedestrian height/hood height was 2.01 ± 0.08, and pedestrian height/(hood height + hood length) was 0.95 ± 0.04 (Table 3).

For the 26 cases in which V < 60 km/h, pedestrian height/hood height was 1.96 ± 0.05 in the 12 cases (46.15%) with pelvic fractures, and the ratio was 2.04 ± 0.08 in the 14 cases (53.85%) without fractures. There was a significant difference between the fractured and nonfractured groups ($P < 0.01$) (Table 4).

There was no significant difference in other fractures (Table 4).

DISCUSSION

The injuries caused by collisions between small cars and pedestrians are very complicated and are related to many factors, such as vehicle speed, collision angle, pedestrian height, pedestrian walking direction, pedestrian reaction, and whether the car brakes before the collision. Although there are currently dummy models,[3] mathematical computer simulations, and other research methods,[4–14] dummy models are not able to reveal pathophysiological changes and are expensive, and it is difficult to reconstruct complex anatomic geometric models and accurately reproduce damage patterns in mathematical computer simulations.[15] In contrast, surveillance videos can theoretically capture the entire process of an accident, including the movement of the human body. Combined with the vehicle paths and autopsy findings, the information from the videos can reveal the collision relationships between vehicles and pedestrians, as well as the correlations between speed, the paths, and human injuries. Compared with other research methods, this method has many advantages, but there are also problems, such as the difficulty in case retrieval and the need to process surveillance video with computers.[18]

TABLE 3. The Height of the Pedestrian, the Height of the Bonnet, the Length of the Bonnet, Pedestrian Height/Bonnet Height, and Pedestrian Height/(Bonnet Height + Bonnet Length) of the 42 Cases in This Study

The Height of the Pedestrian (cm)	The Height of the Bonnet (cm)	The Length of the Bonnet (cm)	Pedestrian Height/Bonnet Height (cm)	Pedestrian Height/(Bonnet Height + Bonnet Length) (cm)
162 ± 6.59	80.74 ± 3.77	90 ± 5.2	2.01 ± 0.08	0.95 ± 0.04

TABLE 4. The Correlations Between Fractures of the Femur, Pelvis, and Ribs and the Ratio of Pedestrian Height to Bonnet Height Under Different Collision Speeds

	Femoral Fractures				Pelvic Fractures				Fractures of the Rib			
The Collision Speed: V	**Yes**	**No**	**t**	**P**	**Yes**	**No**	**t**	**P**	**Yes**	**No**	**t**	**P**
V<60 (26)*	2 ± 0.1 (6)	2 ± 0.07 (20)	−0.263	0.795	1.96 ± 0.05 (12)	2.04 ± 0.08 (14)	−3.179	0.004†	1.98 ± 0.08 (12)	2.02 ± 0.07 (14)	−1.184	0.248
V > 60 (16)	2 ± 0.08 (8)	2.03 ± 0.07 (8)	−0.768	0.455	1.99 ± 0.09 (7)	2.04 ± 0.07 (9)	−1.149	0.270	2.02 ± 0.08 (5)	2.01 ± 0.08 (11)	0.127	0.901

*The figure in brackets represents the number of cases.

† $P < 0.01$, there is a significant difference between the fractured and nonfractured groups.

Because of the unique advantages of surveillance videos, this study used the surveillance videos of 42 traffic accident cases of collisions between small cars and pedestrians crossing the road while braking to determine the characteristics and conditions of pedestrian injuries. In addition, the conclusions of this study can provide references for cases without surveillance video. The data from this study show that the location and degree of injury are related to many factors, such as vehicle speed, collision angle, pedestrian height, pedestrian walking direction, pedestrian reaction, and whether the car brakes before the collision, as well as the height of the hood and the length of the hood.

When V is less than 40 km/h, the pedestrian's head does not collide with the windshield, and the damage to the vehicle is limited to only the front bumper and hood. Fractures of the pelvis and ribs occur in 30% of cases. It has also been reported that severe pelvic fractures can be fatal because of blood loss, with a mortality rate of 32%.[25–27] In this study, there was one case with a collision speed of 70 km/h, but the pedestrian's head did not collide with the windshield. In that case, the ratio of pedestrian height/(hood height + hood length) was 0.87, which was smaller than those in the 31 cases with damage to the windshield and a speed greater than 40 km/h, for which the average ratio was 0.96 ± 0.04 (Table 2). This finding shows that the closer the height of the hood of a small car is to or the more it exceeds the center of mass of the human body, the less likely it is that the head collides with the windshield, but severe pelvic fractures and rib fractures can occur. This finding also reflects the differences in injury characteristics in pedestrians hit by SUVs and small cars.[28,29]

These data from the study indicate that the incidence of pelvic and rib fractures does not necessarily increase with increasing vehicle speed, although there does seem to be a relationship between with height of the pedestrian and height of the hood. When V is less than 60 km/h, the smaller the ratio of pedestrian height to hood height, the higher the incidence of pelvic fractures, although the incidence of femoral and rib fractures did not show significant differences (Table 4). However, when V is greater than 60 km/h, the incidence rates of fractures of the pelvis, ribs, and femurs were not found to significantly differ by the ratio of pedestrian height to hood height.

Frame by frame analysis of two cases was performed, in which the speeds were 47.7 and 70 km/h, the heights of the pedestrians were 165 and 163 cm, the heights of the hoods were 82 and 80 cm, and the pedestrian height/hood height ratios were 2.012 and 2.038, respectively. As a result, the front right part of the small car collided with the left lower limb of the pedestrian at 47.7 km/h, and the torso rotated clockwise while moving toward the hood. The pedestrian's left femur collided with the leading edge of the hood, followed by hip and chest collisions with the hood, which led to fractures of femur, pelvis and ribs. The front left part of the small car collided with the right lower limb of a pedestrian at 70 km/h, and the right lower limb propelled the hip and torso upward, which reduced the magnitude of impact to the pelvis, chest and hood. In other words, the faster the collision speed is, the larger the force of the pedestrian's lower limbs that is directed upward; the collision force of the pelvis and ribs with the hood may be reduced, but the impact of the head and the windshield on the occurrence of head and neck injuries does not decrease. When V is greater than 60 km/h, in addition to severe head injuries, 37.5% of patients suffered from cervical spine fracture, of whom only 12.5% had pelvic fractures, which also supports the above results. Yanar et al[30] also proposed that the incidence of cervical spine injuries after pedestrians are hit by cars increases with the severity of head trauma. Therefore, in the field of forensic medicine and clinical first aid, neck injuries should be considered in addition to head trauma.

In this study, there was 1 case with a speed of 72 km/h but no tibiofibular fractures; the height of the pedestrian was 170 cm, and the height of the hood was 85 cm. According to the analysis of the surveillance video, before the collision, the pedestrian had panicked, moved to avoid the car, and bent their lower limbs, lowering the center of gravity of the body. As a result, the leading edge of the hood directly collided with the buttocks of pedestrian, resulting in a severe comminuted pelvic fracture. This case shows that whether pedestrians have evasive actions can also affect the formation of injuries, and it is very important to pay attention to pelvic or femoral injuries in autopsies and compare them with the collision path of the vehicle.

In the analysis of the surveillance video, this study showed that the upper femur was likely to collide with the leading edge of the hood after the front bumper of the small car collided with the lower leg of the pedestrian. Theoretically, femoral fractures are correlated with vehicle speed, pedestrian height, and hood height. However, the data showed that there were no significant differences between the occurrence of femoral fractures and the ratio of pedestrian height to hood height. Through the analysis of the surveillance video, 1 case in which the left support leg was hit first was found, and the left femur of the pedestrian was fractured in this case. In another case, it was clear that the right nonsupport leg was hit first, and the right femur was not fractured in this case. Although in this study, surveillance videos could be used to determine whether the supporting leg or the nonsupporting leg was hit first in only 2 cases, the results indicated that femoral fractures may be related to which leg is impacted in addition to factors, such as vehicle speed, pedestrian height, and hood height.

In this study, there was also no significant difference between the occurrence of rib fractures and the ratio of pedestrian height to hood height. Rib fractures can be caused not only by direct collisions with the hood but also by falls to the ground. It is difficult to distinguish the 2 causes of fractures through surveillance video analysis and autopsy, which is also one of the limitations of this study. There are several limitations in this research: (1) Through the analysis of the surveillance videos, combined with trace inspection and system anatomy, it is possible to assess specific aspects of a collision between a small car and a pedestrian, especially the relationship between the vehicle and the pedestrian's lower limbs, pelvis and head upon collision; however, fractures of skull, pelvis, and ribs are also easily formed or aggravated during falls to the ground, so there may be some discrepancies in the AIS injury score. (2) In China, not all deceased resulting from traffic deaths have complete autopsies because of the factors related to the police system, customs, and economic conditions. In particular, most cases with clear surveillance videos and clear accident processes do not receive complete autopsy examinations. Therefore, some surveillance videos in this study are affected by factors, such as poor angles and lighting, which is also the reason why whether the supporting leg was hit first could only be determined in 2 cases. In addition, the sample size of this study is small, and the sample size will continue to be expanded in the future for further research. (3) When small cars brake, the head of the car exhibits a “nodding motion,” which decreases the height of the hood by 5 to 10 cm compared with that in the flameout state. In this study, the height of the leading edge of the hood was measured in the flameout state, so there may be a 5- to 10-cm difference between the measured value and that in the actual collision. (4) This research is based on actual cases and lacks consideration of some possible influencing factors, such as body position, car type, car weight, road conditions (wet, dry), and so on. These factors will also be included in the study in the follow-up work (Supplementary material, http://links.lww.com/FMP/A41).

CONCLUSIONS

Surveillance videos are important for studying the process of traffic accidents and the mechanisms of traffic injuries. In collisions between small cars and pedestrians, the formation of human injuries is related to not only the speed and angle of the collision but also to the height of the pedestrian, the height of the hood, the length of hood, and whether the car braked before the collision.

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