Fatal Motor Vehicle-Pedestrian Collision Injury Patterns—A Systematic Literature Review

Moheem Masumali Halari and Michael James Shkrum

ABSTRACT

Introduction: Injury patterns in pedestrians struck by motor vehicles were described in medical literature first published almost a half century ago. "Classical" triads of injury distribution were described for adults (skull-pelvis-extremity) and subsequently applied to children (head-hip or pelvis-distal femur/knee joint). Notably, these classical triads were derived from two publications reporting clinical observations of only 11 patients, all of whom were adults. **Methods:** A systematic literature review was conducted using Medline, CINAHL, EMBASE, and Cochrane to determine the evidence-base for motor vehicle collision (MVC)-pedestrian injury "triads" and other trauma patterns described for pedestrians in the adult and pediatric age groups. **Results:** Of the 1540 full-text articles identified in the review, 56 articles published in English met the inclusion criteria, that is, motor vehicle-pedestrian collision resulting in specific, fatal injuries determined by postmortem examinations. There were variations in injury patterns that differed from the "classical" triads. These differences likely stem from advances in vehicle design and safety features which have affected the nature and distribution of injuries. **Discussion:** Further research on the correlation of specific injuries sustained by pedestrians of different ages with various types of vehicles and impacts are needed to assess the validity of previously observed injury patterns in relation to the current motor vehicle fleet. Delineation of injury patterns can assist health care teams in trauma management. Vehicle manufacturers and government regulators can better assess whether the introduction of advanced driver assistance features designed to protect pedestrians when struck will be effective in reducing severe injuries. In forensic pathology practice, knowledge of pedestrian injury patterns based on data representative of impacts involving modern vehicles can provide MVC death investigators the means to determine MVC dynamics and pedestrian kinematics.

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NOTE

The United Nations has defined "youth," as individuals between 15 and 24 years of age and "children" under the age of 14 (81). The "elderly" have been defined as individuals aged 65 and above (82,83).

KEYWORDS

Forensic pathology, Pedestrian, Motor vehicle collision, Injury pattern, Injury triads, Literature review

INFORMATION

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INTRODUCTION

The United Nations reports that yearly 1.25 million fatalities occur worldwide due to motor vehicle collisions (MVCs), nearly half of which involve vulnerable road users (VRUs), that is, pedestrians, cyclists, and motorcyclists (1). There are approximately 45,000 traffic deaths annually in the United States of which pedestrians and motorcyclists account for 15% (2). In Canada, there were 1922 motor vehicle fatalities in 2018 of which pedestrians accounted for 17.3% (332 cases) (3).

The 2018 Annual Road Safety report by the International Traffic Safety Data and Analysis Group (IRTAD) revealed an increase globally in the frequency of fatally injured pedestrians as a proportion of all road traffic fatalities from 22% in 2010 to 24% in 2016 (4). In Canada, the largest increase in MVC-related fatalities in 2016 was registered among pedestrians with 21.1% more road deaths in 2016 compared to 2015 (5). The 2019 Road Safety report showed an apparent 13.3% decrease in pedestrian deaths in 2017 compared to the previous year, but this observation was based on preliminary data (6). Using the Transport Canada's National Collision Database for collisions involving one or more pedestrians, the total number of pedestrian fatalities to the number injured for 2017 was 2.7% (316/11691), 2.9% in 2016 (379/12899), and 2.5% in 2015 (325/12906) (7). This data indicated there was a 16% increase in the number of fatalities relative to the number injured from 2015 to 2016, but an encouraging 7% decrease from 2016 to 2017. In the United States, an increase of 9.0% was noted among pedestrian fatalities for the same time period (8). According to the 2018 and 2019 annual Road Safety report, the rise in pedestrian deaths could be due to increasing number of pedestrians walking longer distances between 1990 and 2017, according to the National Household Travel Survey (9). According to Parachute Canada, one of the leading causes of injury-related deaths for children aged 14 years and younger is MVC-pedestrian trauma (10). According to Transport Canada's National Collision Database Online 1.0 for children (0-14 years), the total percentage of pedestrian fatalities (collision involving one or more pedestrians) relative to the number of pedestrians injured in 2017 was 1.7% (fatal 17, injured 996), 1.4% in 2016 (fatal 15, injured 1071), and 1.0% in 2015 (fatal 12, injured 1153). This trend shows a rise in the relative proportion of deaths to injured in this age group (7). In the United States, the National Highway Traffic Safety Administration in 2016 noted that 20% of all fatal traffic accidents were pedestrians aged 14 and younger (11).

Delineation of trauma from MVC-pedestrian collisions into injury patterns has meant focused medical management directed to serious and life-threatening injuries (12-14). In 1962, McCarroll et al. suggested that trauma management focusing on injuries of the head, pelvis, and lower extremities would lead to relatively longer survival of patients (15). They based their suggestion on a study of 200 cases MVC-pedestrian fatalities. The authors stated that by vigorously treating head, pelvis, and lower extremity injuries, complications such as subdural hemorrhage and pulmonary thromboembolism could be treated expeditiously or prevented. In forensic pathology practice, knowledge of MVC-pedestrian injury patterns allows correlation with vehicle impact dynamics and the resulting pedestrian kinematics which can assist MVC investigations by police (16); however, the current understanding of the types and distribution of injuries that can occur is based on observations made almost a half century ago.

In 1962, Slätis described injuries in drivers, passengers, motorcyclists, bicyclists, and pedestrians involved in fatal traffic accidents (17). Pedestrian injuries were described as primary, that is, initial impact usually by bumper, radiator, or front mudguard and secondary, that is, subsequent impact with the ground or an object not otherwise specified. Primary trauma involved the lower extremity, pelvic girdle, chest and spine, and secondary injuries were to the head (17).

In 1965, "The Fatal Triad" of skull-pelvic-extremity fractures was described by Farley (12). In this article, he described a patient who survived this pattern of injuries which was associated with intracranial and retroperitoneal hemorrhages and referred to a "... recent

Table 1: Injury Patterns Identified From Literature Review.

Authors	Study period	Number of cases	Age range in year/gender (#= no. of cases)	Injury pattern
Farley (12)	1965	Unknown	Unknown	Skull-pelvis-extremity fracture
Waddell and Drucker (13)	1971	10	21-74/ Male (4) and Female (6)	Knee-hip/pelvis-craniocerebral injury
Garland et al. (21)	1979	25	15-59/ Male (17) and Female (8)	Craniocerebral injury-pelvic fracture-lower extremity injury
Brainard et al. (19)	1992	115	1-84/ Male (83) and Female (32)	Ipsilateral dyad (upper and lower extremity fracture) and femur fractures co-existed with pelvic fractures.
Williams et al. (22)	1995	223	0-90/ Male (152) and Female (71)	Cervical spine, heart, aorta, liver, extremities, pelvis, ribs, and thoracic spine
Orsborn et al. (14)	1999	465	13 months-19/ Male (306) and Female (159)	Head and leg injury = 78
Reith et al. (20)	2015	4435	49.1 $\pm$ 25.0/ Male (2572) and Female (1863)	Head, chest and lower extremity injuries

review of such cases over a three-year period at the Hennepin County General Hospital . . . " He did not provide any further information about these cases.

In 1971, a "predictable" pattern comprising knee (distal femur-knee joint-proximal tibia), hip, or pelvis and craniocerebral injuries was identified by Waddell and Drucker ("Waddell's triad") in ten patients, one of whom died (13). The authors did not mention whether this person was autopsied.

In the same year, Van de Voorde et al. described the injuries sustained by pedestrians based on vehicular impact zones (right side, left side, front, and rear) (18). The authors divided injury mechanisms into first- and second-degree impact injuries, falls onto road surfaces, and "slide traces" a term which was not further defined. These authors categorized the initial impact, typically with the bumper, as first-degree. Subsequent impacts with other surfaces of the vehicle such as the hood were second-degree impacts. The authors did not mention ground impacts. They noted that lower extremity contusions with subcutaneous hematomas were indicative of vehicle bumper height and important findings for the collision reconstruction (18).

Since these early publications, various articles have identified other injury patterns that differ from the "classical" triads derived from the descriptions of Waddell and Drucker, and Farley (**Table 1**) (14,19,20).

Researchers recognized that one factor that accounted for differences in injury patterns and their severity was vehicle bumper design. Robertson compared fatal pedestrian injury rates from vehicles manufactured between 1980 through 1985 that either had sharp front edge corner or smooth front designs (23). He found that the risk of death was 26% higher for pedestrians involved in collisions with vehicles that had a sharp front corner. In 1973, a reference to bumper impact injuries was noted in English literature describing pedestrians who sustained lower extremity fractures when struck upright (24). "Bumper fractures" typically involve the tibia and fibula (16,25-27). The complexity of fractures, that is, comminuted or transverse/oblique due to protruding or rounded bumpers, respectively, has been observed, and alteration of bumper design can lower the incidence of complicated fractures (28). Varying the height of vehicular bumpers can result in differences in the level of lower extremity injuries (29).

In 1979, Garland et al. also described a triad of craniocerebral injury, pelvic fracture, and lower extremity injury. They also wrote that two different mechanisms, dependent on the profile of the vehicle, accounted for differences in the lower extremity injuries when compared to Farley's and Waddell's triads (21). Garland et al. opined that the bumper of a lower profile vehicle tended to primarily impact the lower leg followed by secondary impact of the head on the hood. A pelvic fracture may not occur. In contrast, an impact with the bumper and hood of a high-profile vehicle could injure the knee and pelvis, respectively, and then head and shoulder trauma from ground impact could follow (21). Other authors challenged the injury pattern of the original triad attributed to Waddell and Drucker.

In 1992, Brainard et al. described the "ipsilateral dyad" consisting of fractures of the upper and lower extremity on the same side. They also noted that femur fractures coexisted with pelvic fractures (19). Of the 115 cases individuals in their study, who ranged in age from 1 to 84 years old, only 10 cases had injuries matching the original description of Waddell's classical triad (19). The authors did not specify the age group of these 10 cases.

In 1999, Orsborn et al. observed that of 465 pediatric pedestrians struck by motor vehicles, 234 did not suffer a head injury (14). Of the other 231 who had a head injury, 78 had a combination of head and leg injuries. Orsborn et al. also noted that there were varying descriptions of Waddell's triad in the medical literature from 1971 until 1998. They found that 2.4% (n = 11) cases fell into a variation of Waddell's triad consisting of head, leg, and abdominal injury, and only 0.02% (n = 1) had injuries of the classical triad. This considerable discrepancy is explained by the misapplication by other authors of Waddell's and Drucker's observations of injuries in their ten patients, who were aged 21 to 74 years, to the pediatric age group.

In 1995, Williams et al. identified injury patterns in pedestrians under the influence of alcohol that were different, more serious, and more rapidly fatal than those seen in sober pedestrians (22). They observed a greater frequency of injury involving the cervical and thoracic spine, chest wall, heart and aorta, liver, and upper and lower extremities.

In 2015, Reith et al. confirmed that variations in injury patterns depended upon factors related to the motor vehicle such as type of impacting vehicle, site of primary impact, and its direction (20). They identified in their study a combination of head, chest, and lower extremity injuries as the predominant (16.3%) injury pattern. They wrote that they could not "identify" the triads described by Farley, and Waddell and Drucker and that these "classical" triads had "less relevance" to current MVC-pedestrian impacts (20). The purpose of the present study was to determine the evidence-base for MVC-pedestrian injury "triads" and other trauma patterns described for pedestrians in the adult and pediatric age groups based on a systematic literature review.

MATERIALS AND METHODS

A systematic literature review was conducted using Medline, CINAHL, EMBASE, and Cochrane. All databases were searched using Medical Subject Heading (MeSH)/Boolean/Map term/Keywords: "Accident, Traffic" AND "Pedestrian." The results from each database were then extracted into Rayyan QCRI (Qatar Computing Research Institute) an online systematic review web-based application (30). After identifying and excluding duplicates, the title and abstracts were screened by the authors independently using the blind mode. The PRISMA 2009 flow diagram (**Figure 1**) was followed and inter-rater agreement was assessed using Cohen's kappa. Disagreements were discussed and resolved by reaching a consensus.

Full-text articles in English language were assessed when the inclusion criteria were met, that is, motor vehicle-pedestrian collision (MVPC) resulting in specific, fatal injuries based on autopsy findings. Articles were excluded if injured pedestrians were in wheelchairs/prams, struck by trains/trams, snowmobiles, or involved in nonmotorized collisions (e.g., horse rider, cyclist). Studies that used postmortem human subjects to simulate an injury pattern were also excluded. Articles that indicated Abbreviated Injury Scale and Injury Severity Score but did not specify injuries were excluded.

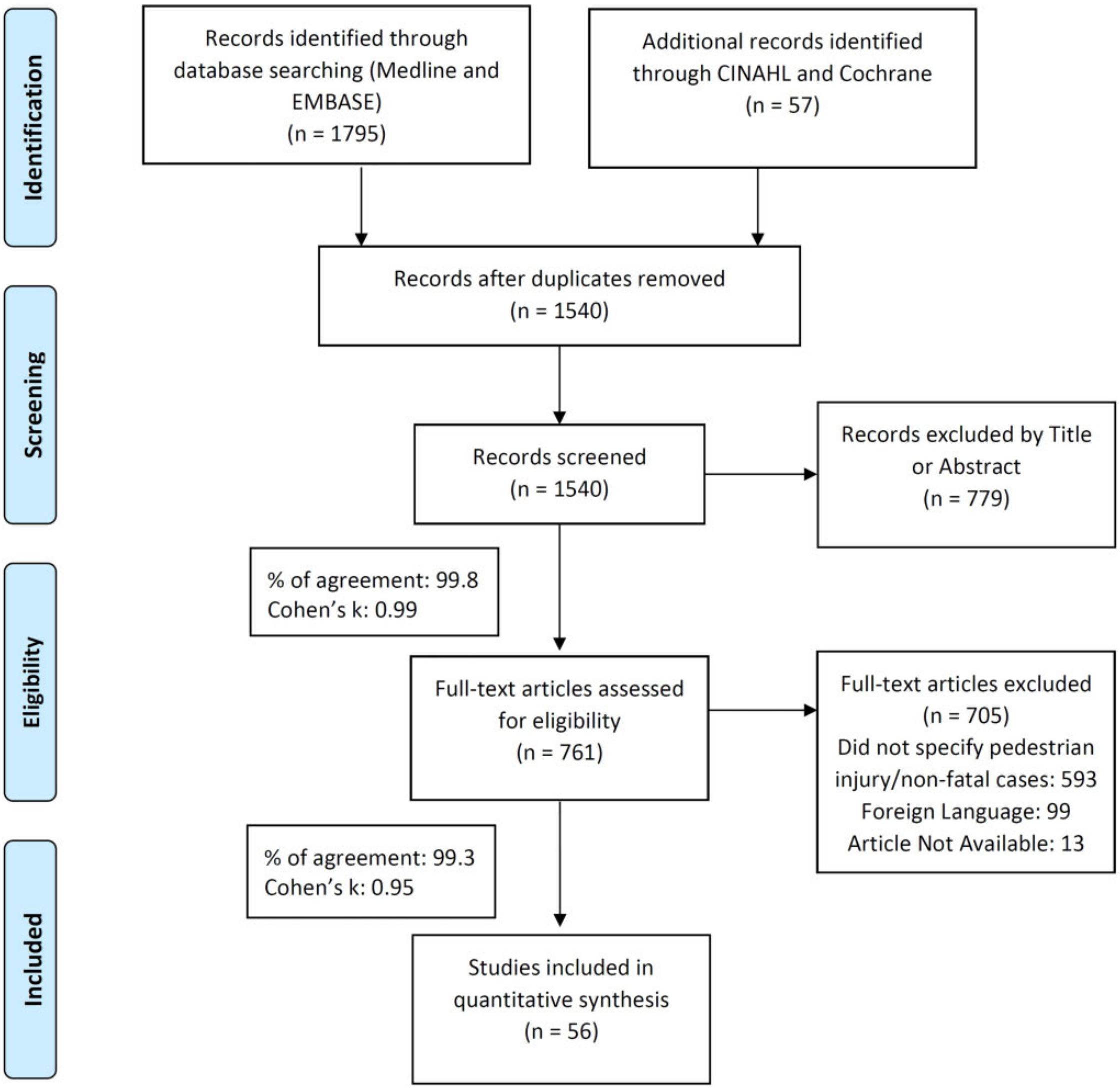

Figure 1: Study selection using PRISMA flowchart.

RESULTS

Of the 1540 articles identified in the review, the following 56 articles met the search criteria (**Figure 1**) (17,18,25-27,22,31-80).

Study Period

Thirty-two (57.1%) articles indicated a study period, ranging from 1 year to 23 years (17,18,25,27,22,31-36,38-46,48-51,53-57,77,79,80). Out of 16 case reports, 4 indicated a study period (**Figure 2**) (37,47,52,78).

Of the 36 articles with defined study periods, 4 were case reports, and the other publications had sample sizes between 4 and 470 individuals. Eleven articles had a sample size of 200 or more. The most common combination of injuries identified in a study of 470 pedestrians in 1975 were head, thorax, and lower extremity (fracture of tibia and fibula) (80). Of 469 cases described in 1991, the head,

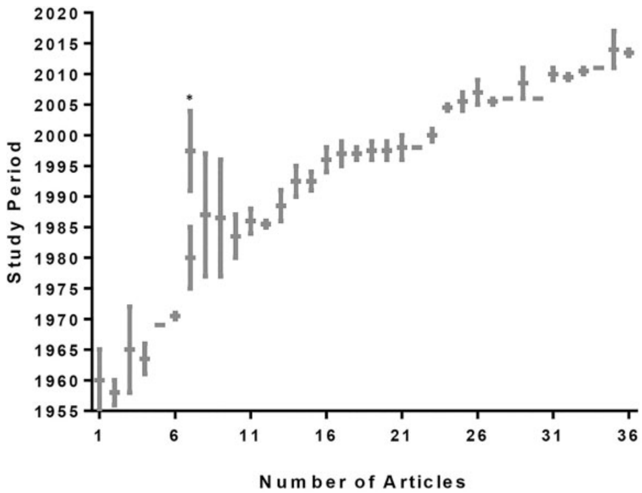

Figure 2: Thirty-six articles with specified study periods. Single horizontal lines represent one year of study; four were case reports involving a single fatality (37,47,52,78). Vertical lines represent length of study and their intersecting horizontal lines their medians. * This 23 year study was based on 2 intervals (1975-1985 and 1991-2004) (44).

thorax, and abdomen were most commonly injured (32). In two publications that used data from the same 371 cases examined in the Department of Forensic Medicine in Lublin, Poland, Teresinski et al. concentrated on isolated injuries—soft tissue (27) in 2002 and pelvic (40) in 2001. Another article in 2005 by Toro et al. focused on head injuries seen in 371 cases examined in the Forensic Institute in Budapest, Hungary (43). All three of these articles did not define injury patterns. Of 309 cases in a study published in 2017, the most common combination of injuries were head and thorax injury (45). Injuries described from this more recent publication were less reflective of the modern vehicle fleet because the database comprised road traffic fatalities who died in 2004 and 2005. Similarly, another article published in the same year used data from 254 cases from 2006 (48). Two articles that were published in 2018 did include recent cases but had smaller sample sizes of 21 and 33 cases, and the authors focused on radiologic imaging and cardiac injuries, respectively (56,57).

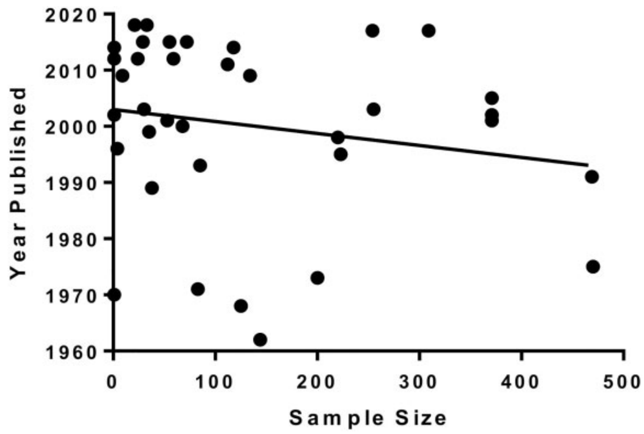

Figure 3: Comparing publication date to sample size for the 36 articles.

Sample Size and Origin

The sample sizes in the 36 articles that specified study periods ranged from single case reports to 470 individuals (**Figure 3**). The total number of subjects in these articles were 4477. The more recent studies trended to case reports and smaller sample sizes.

The types of studies were retrospective (39.3% [n = 22]), case reports (28.6% [n = 16]), unknown (26.8% [n = 15]), prospective (3.6% [n = 2]), and case control (1.8% [n = 1]). They originated from 22 countries. Studies in five countries contributed to over half of the publications. Publications using American data accounted for 19.6% (n = 11) (22,31-33,35,39,46,72,75,76,78), Germany and Poland 10.7% (n = 6) each (25-27,38,40,42,44,45,59,60,64,65), and India and Switzerland 8.9% (n = 5) each (47,48,50,51,53,54,56,57,62,70). Of the 22 countries represented in the reviewed publications, the majority were from countries where drivers drove on the right side of the road (n = 15; 68.2%) compared to those where traffic flow was on the left (n = 7; 31.8%). There were no other studies from other North American countries. Data for these publications were derived from Forensic/Legal Medicine Department/Institute/Coroner/Medical Examiner Records.

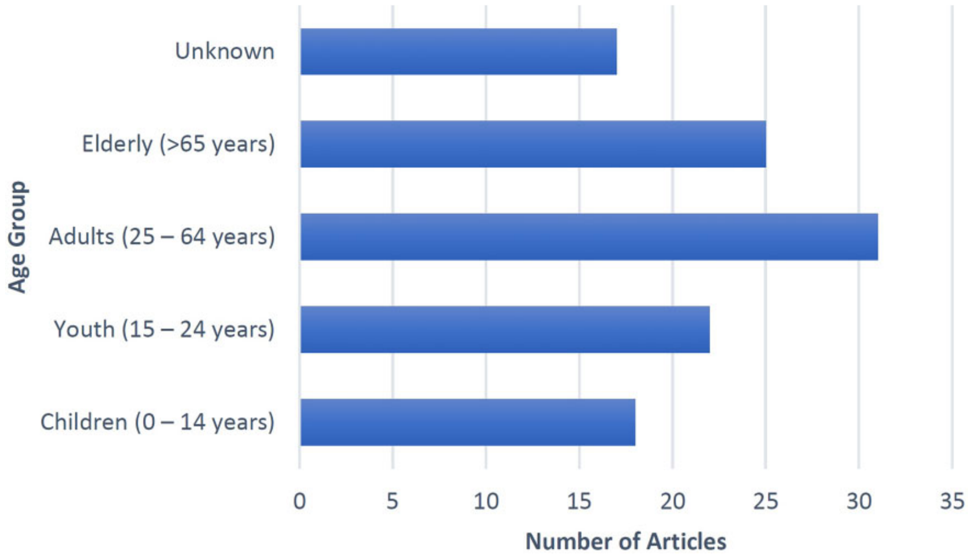

Figure 4: Age groups represented in the literature.

Age and Gender

Injuries were described in adults (25-64 years) (55.4% [n = 31] of the articles) followed by the elderly (≥ 65 years) (note 1) (44.6% [n = 25]). Children (0-14 years) (note 1) and youth (15-24 years) (note 1) were each described in 32.1% (n = 18) and 39.3% (n = 22), respectively of the total number of articles (**Figure 4**). In 42 articles (75%), the age groups were intermingled, and injury patterns could not be distinguished based on age. Fourteen articles (25%) indicated a single age group. There were nine for adults (37,47,58,61,63, 66-68,76), three for elderly (34,59,60), one for children (78), and one for youth (71). Adults sustained injuries to all body locations the most common being head/face/neck (88.9%, n = 8), upper extremity (77.8%, n = 7), lower extremity (77.8%, n = 7), and spine (66.7%, n = 6).

Gender was indicated in 39 articles (69.6%) (17,25,22,31-34,36,37,42,44,45,47,50,52-54,57-74,76,77,79,80). Males only were specified in 17.9% (n = 10) (37,52,58,60,66-69,71,76) and females only in 10.7% (n = 6) (34,47,59,61,63,74) of the articles. Both genders were mentioned in 23 articles (17,25,22,31-33,36,42,44,45,50,53,54,57,62,64,65,70,72,73,77,79,80). Seventeen publications did not indicate gender.

Table 2: Data From Medicolegal Settings.

	Medicolegal (n, %)
Age group:	
Children (0-14)[a]	18, 32.1%
Youth (15-24)[b]	22, 39.3%
Adults (25-64)[c]	31, 55.4%
Elderly (≥ 65)[d]	25, 44.6%

Abbreviations: n, number of articles; %, percentage of articles.
[a](17,25,22,31-33,36,42,50,54,64,65,70,73,74,78-80).
[b](17,25,22,31-33,36,42,44-46,50,53,54,62,64,65,70,71,73,79,80).
[c](17,25,22,31-33,35,37,44-47,50,53,54,57,58,61-68,70,72,73,76,79,80).
[d](17,25,22,31-35,44,45,50,53,54,57,59,60,62,64,65,70,72-74,79,80).

The adult and elderly age groups were more frequently described in the literature derived from data in medicolegal settings (**Table 2**). Overall, head, face, and neck injuries were the most common (71.4%, n = 40) followed by thorax (64.3%, n = 36), and head trauma was the most common cause of death.

Type of Vehicle and Impact Area

Thirty-seven (66.1%) articles indicated a type of vehicle (17,18,25-27,22,31-33,36-38,40,42,44,47,50,52, 53,57-61,63-72,74,78,80). Twenty (35.7%) articles stated the impact site on the vehicle (18,25, 27,31,33,36,37,44,47,52,57-60,66,68-70,74,78). Cars predominated in 33 (58.9%) articles (17,18,25-27,22,31-33,36-38,40,42,44,50,53,57-61,63-65,67-72,74,80), followed by truck/bus/coach/lorry and vans in 19 (33.9%) (17,18,27,22,31-33,36,38,40,42,47, 50,53,57,66,72,74,78) and 10 (17.9%) articles (18,27,22,31-33,38,40,53,74), respectively. Of the articles that mentioned both the vehicle type and impact site, cars were most frequently described in 16 (80%) (18,25,27,31,33,36,37,44,57-60,68-70,74) followed by truck/bus/coach/lorry, and vans in 10 (50%) (18,27,31,33,36,47,57,66,74,78) and 5 (25%) (18,27,31,33,74) articles, respectively. The front of the vehicle was the most common impact site in 10 (50%) articles (18,25,27,33,44,47,57,69,70,74).

Most Common Injury Locations

Thirty (53.6%) articles specified the most common injury locations (**Table 3**). The most common combination of injuries was identified in 16 (53.3%) articles. Head and upper/lower extremity injury, head, thorax, upper/lower extremity injury, and head and thorax injury were equally described (3 [18.8%] articles each). The most common isolated injury locations were identified in 14 (46.7%) articles. Head injury predominated in 5 (35.7%) articles. There was only one article that described a classical triad of injuries, that is, head, pelvis, and lower extremity (41).

Of the 56 articles, only 10 articles in the present review indicated that radiological findings supplemented autopsy observations (22,35,37,39,53,57,58,61, 62,70). Teresinski et al. mentioned the use of radiology to diagnose injuries for accident reconstruction in two articles but whether imaging supplemented their studies was unclear (27,40). Heinrich et al. studied 309 cases who died in 2004 and 2005 and had postmortem examinations. They wrote that postmortem computed tomography (CT) imaging was not done routinely during the study period; therefore, certain injuries to the facial bones, spine, pelvis, and extremities may have been underrepresented in the study (45).

Table 3: Most Common Isolated and Combination of Injuries Identified.

Injury location	Number of articles
Head Injury (42,43,49,55,74)	5
Head and upper/lower extremity injury (31,48,77)	3
Lower extremity injury (26,65,75)	3
Head, thorax, upper/lower extremity injury (22, 79, 80)	3
Head and thorax injury (17,45,54)	3
Thorax injury (35,56)	2
Superficial Injury (27)	1
Spine injury (51)	1
Head, pelvic and lower extremity injury (41)	1
Face injury (73)	1
Pelvic injury (40)	1
Head and spine injury (57)	1
Thorax, pelvic and lower extremity (25)	1
Head, thorax and abdominal injury (32)	1
Head, neck, thorax, pelvic and lower extremity injury (44)	1
Head and neck injury (50)	1
Head and abdominal injury (36)	1

Injuries Sustained by Types of Vehicles and Impacts

There were 19 articles (33.9%) that indicated a single vehicle type (25,26,37,44,47,52,58-60,63-69,71,78,80) of which 15 articles (79.0%) specified car (25,26,37,44,58-60,63-65,67-69,71,80). The adult ($n = 10$, 66.7%) and elderly ($n = 7$, 46.7%) age groups predominated when car impacts were involved (**Table 4**). Lower extremity ($n = 13$, 86.7%) and head/face/neck and spine ($n = 11$, 73.3% each) injuries were the most common type of trauma described that resulted from car impact.

Table 4: Data From Articles Describing a Single Vehicle Type.

	Car, (n, %)	Truck/bus, (n)	Light utility /SUV, (n)
Age group:			
Children (0-14)[a]	4, 26.7%	1	0
Youth (15-24)[b]	6, 40.0%	0	0
Adults (25-64)[c]	10, 66.7%	2	0
Elderly (≥ 65)[d]	7, 46.7%	0	0
Unknown[e]	2, 13.3%	0	1

Abbreviations: %, percentage of articles; n, number of articles; SUV, sports utility vehicle.
[a]Car (25,64,65,80), Truck (78).
[b](25,44,64,65,71,80).
[c]Car (25,37,44,58,63-65,67,68,80), Truck (47,66).
[d](25,44,59,60,64,65,80).
[e]Car (26,69), SUV (52).

Only 3 articles (15.8%) involved a truck or bus as the only type of vehicle (47,66,78). Although these articles described injuries, they did not indicate the most common injury locations.

There was a single article involving a sports utility vehicle (SUV) (5.3%) and even though trauma was described, the most common injury location was not mentioned (52). Although there were articles that included vans, they did not separate them from other vehicles in these studies.

Car impacts were either right frontal (n = 5, 62.5%) (37,58-60,68) or frontal (n = 3, 37.5%) (25,44,69). Five of the 19 articles (26.3%) (25,26,44,65,80) indicated the most common injury locations of which lower extremity (n = 2, 40.0%) (26,65) was the most common.

Injuries Sustained Based on Impact Zone for All Types of Vehicles Involved

There were 18 articles (32.1%) that specified an impact zone and correlated it with injuries (18,25,27,31, 33,36,37,44,47,52,57-60,66,69,74,78). Nine articles (50.0%) specified frontal impact alone (18,25,27,33, 44,47,57,69,74). The adult (25,33,44,47,57) and elderly (25,33,44,57,74) (n = 5, 55.6% each) age groups predominated. Five articles (27.8%) indicated right frontal impact alone (37,52,58-60). Three articles (16.7%) described rear impact alone (31,36,66). Only 1 article (5.6%) described a side impact alone (78).

Injuries Sustained Based on Impact Zones for Cars

There were only 11 articles (19.6%) that specified the impact zone for a vehicle type and correlated with trauma (25,37,44,47,52,58-60,66,69,78). Seven of these articles (63.6%) described cars that had right frontal (n = 4, 57.1%) (37,58-60) and frontal (n = 3, 42.9%) impacts (25,44,69). Right frontal impacts resulted in injuries most commonly of the head, face and neck, lower extremity and spine, and frontal impacts more frequently involved the lower extremities and spine.

DISCUSSION

Since the first fatal MVPC in 1896 (84), only 56 of the 1540 articles found by the authors in the present systematic review of peer reviewed publications in the English language medical literature specified injuries observed at autopsies of pedestrians who were struck by motor vehicles. Mackay wrote that details about MVPC during the late 1960s were only available in police investigation files and hospital records, and this restriction of information meant there was inadequate data to correlate pedestrian injuries with collision dynamics and pedestrian kinematics (85). For example, Karger et al. could not determine how impact geometry, collision speed, or pedestrian movement played a role in their study because these factors were unknown (25). Even basic information such as the type of collision was lacking (25).

Until 1962, only two articles used autopsy findings to determine the totality of the fatal injuries sustained by VRUs including pedestrians (17,86). Huelke et al. emphasized that necropsies were needed to understand the mechanism of injuries occurring in automobile fatalities (86). Postmortem examinations can be further enhanced by radiologic imaging (CT scans) by discovering subtle findings not seen during a conventional autopsy. Only 10 articles in the present review incorporated radiologic findings (22,35,37,39,53,57,58, 61,62,70).

Questioning the relevance to forensic pathology practice of the "classical triads" observed by Farley, and Waddell and Drucker is pertinent given that the present review found that various patterns of motor vehicle-pedestrian trauma have emerged since the descriptions by these authors of a limited number of mostly nonfatally injured patients who were seen in clinical settings five decades ago. Much of the medical literature is based on clinical studies of patients admitted to hospital. There are relatively few publications relevant to forensic pathology practice found in this systematic review, and this is a limitation that continues to the present day.

Of the 36 articles that indicated a study period, 13 of them were published in the past decade (2010 onward) (41,45-48,50-57) and ranged from single case reports up to 309 fatally injured pedestrians. Of these apparently more contemporary studies, those with larger sample sizes had limited applicability to trauma observed in the current MVPC. Although the study of 309 cases was published in 2017, the injury patterns were seen in individuals autopsied in 2004 and 2005 (45). Another study of 254 pedestrians that was published in 2017 had a similar drawback because the injury patterns were observed from cases examined in 2006 (48).

Compared to older studies performed (27,32,40, 43,80), many later studies had shorter study periods and decreasing sample sizes that did not lend themselves to statistical analysis (46,47,50-57). Most of the articles (17,18,26,31,32,36,38-40,42,44,46,48-51,53-57,62,67,76,77,79,80) presented results using frequency tables that could have benefitted from the use of advanced statistical analysis to better identify injury pattern trends in relation to MVCs (25,27,22,33-35,41,43,45,61,64,65,73). Another shortcoming of these larger studies was that the injury patterns were generalized within the entire sample size.

There were only 14 articles linking injury distribution to pedestrian age. In the present literature review, adults were the most frequent age group described followed by the elderly. Head/face/neck, thorax, pelvis, spine, and lower extremity were common injury locations for all age groups. Injury locations in the pediatric age group described in the literature appeared to be variations of adult patterns and were not accurately captured by the so-called "Waddell's triad" that was originally based on the trauma seen in ten adults described in the original paper (13).

In 1967, William Haddon informed the National Highway Safety Bureau (now known as National Highway Traffic Safety Administration) that vehicle designs were factors affecting the severity of injuries in pedestrians struck by MVCs (87,88). Our systematic review found that less than a quarter of the publications (11 of the 56 articles) were based on observations of MVC-pedestrian collisions involving the North American fleet in the United States. The implication of this shortfall is that there are too few articles that link fatal injury patterns with design and safety features currently available in the North American fleet that differ from vehicles manufactured in Europe. For example, comparison of American and European standards for mitigation of leg injury from bumper impact showed that the latter offered better protection (89).

Eighteen of the included articles indicated various vehicle types in their study but did not indicate injuries sustained by pedestrians specific to vehicle type. Nineteen articles did not even mention a vehicle type. The most frequent vehicle type and impact zone described in the literature were cars and frontal impacts, respectively. Understanding injuries sustained by pedestrians in relation to vehicle types other than cars is lacking in the medical literature. There were very few articles describing injuries caused by trucks, buses, vans, and light utility vehicles/SUVs that correlated pedestrian and the features of these vehicles to pedestrian injuries. This is a major deficiency because vehicles, other than cars, represent a significant part of the North American fleet. A half million vans and over 8 million SUVs were sold in 2019 (90,91).

There was only one article found in the present literature review that described an injury pattern similar to Farley's triad (41). There were no articles that described Waddell's triad based on medicolegal data. Whether the historical triads and other injury patterns which have subsequently emerged are applicable to trauma observed in the current motor vehicle fleet requires further research.

CONCLUSION

In summary, understanding the types and mechanisms of specific injuries, particularly in different age groups, by correlating them with collision dynamics and pedestrian kinematics observed in the current vehicle fleet can contribute to clinical trauma management, collision reconstruction by police, medicolegal death investigations, and motor vehicle design, particularly regarding the efficacy of advanced driver assistance systems in the mitigation and prevention of serious injuries.

The literature review revealed that the distribution of injuries in pedestrians had changed since the "classical triads" were described almost 50 years ago. Whether this evolution reflects the idiosyncratic and seemingly random nature of MVPCs because of the multitude of vehicle, crash and pedestrian variables involved or truly reflects evolving injury patterns requires more research. At least, the description of injury "triads" and "dyads" recognized that MVPC were complex events involving multiple impacts with vehicle exteriors resulting in a wider spectrum of injuries that needed to be addressed during clinical assessment and management. Any future studies of fatal MVPCs need to correlate injury patterns based on age groups, gender and height of the pedestrian and integrate this information with a range of vehicle types, their impact speeds, sites of pedestrian impact on those vehicles, vehicle designs including bumper heights and driver maneuvers (e.g., turning, braking/no braking) at impact.

This literature review revealed that vehicle and crash information was limited in the data derived medicolegal death investigations and postmortem examinations. This gap highlights the need to integrate trauma and vehicle crash data through access to police reports. Ideally, this could be accomplished by a standardized MVPC death investigation report that recognizes a team approach to MVPCs. This would create a better understanding of how these injuries occur and could assist in developing automobile safety features that would mitigate injury severity.

Any future study requires an adequate number of cases to allow more meaningful statistical analysis in stratifying injury patterns to the aforementioned pedestrian and vehicle factors. Determination of injury patterns in fatal cases is best derived from data from complete autopsies which can be further enhanced by radiologic imaging. Comparison of injury patterns between fatal and nonfatal cases may also assist in understanding how certain factors, other than those that are intuitively obvious (e.g., vehicle speed), such as vehicle design and advanced driver assistance features, may affect injury severity.

Limitations

The MeSH terms used for our study ("pedestrian" and "accident, traffic") did not find the seminal publication by Farley because his MeSH terms in PubMed (Fractures, Bone, Minnesota, Pelvic Bones, Pelvis, Skull, Wounds, and Injuries) did not include pedestrians and specify the origin of the injuries. Waddell and Drucker's paper did include the MeSH term "accident, traffic" and was found in the systematic literature review; however, it did not mention whether an autopsy was done on the single fatality in the author's series.

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