Pedestrian Injury Analysis: Field Data vs. Laboratory Experiments

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Abstract This study aims to present all of the injuries sustained by 17 post-mortem human surrogates (PMHS) tested in vehicle-pedestrian impact experiments and explore the injuries, their sources, mechanisms and clinical relevance by comparing them to injuries sustained by 24 PMHS from previous literature and by the pedestrians that were entered into a recent in-depth database of vehicle-pedestrian crashes. The 17 PMHS were tested in lateral impact by one of five late-model production vehicles at 40 km/h in a controlled laboratory setting and all of their injuries were examined in detail. The Crash Injury Research and Engineering Network (CIREN) program enrolled 67 US vehicle-pedestrian crash cases between 2002 and 2007, and in-depth analysis of the pedestrians' injuries, injury mechanisms and sources was conducted by a team of biomechanical engineers, crash investigators and trauma physicians. The PMHS tests resulted in greater frequency and severity of spinal injuries, pelvic injuries and knee injuries than in the case studies, partially due to age and bone quality of the PMHS, and partially due to the effect of active musculature. Both the PMHS and the case studies showed that sustaining a knee or leg injury in one lower extremity protects against sustaining a concomitant leg or knee injury to the same lower extremity.

Keywords Pedestrian, Cadaver, CIREN, Injury, PMHS

I. INTRODUCTION

Pedestrian injury and fatality resulting from vehicle crashes is a worldwide public health problem. Researchers have long understood that the severity of injuries sustained by pedestrians in vehicle impacts is sensitive to vehicle front end design and that designs can be adjusted, or even optimized, for pedestrian safety [4]. But to understand how specific vehicle designs affect injury type, injury mechanism, source and severity three paths are possible: computational simulations with mathematical models of the vehicles and pedestrians, experimental tests with post mortem human surrogates (PMHS) or crash dummies, or retrospective examinations of crash, vehicle and pedestrian parameters from crash databases. While recent advancements in computational technology have provided for the development of highly detailed mathematical models of the human body, which will likely result in advancements of prospective crash injury research methods, the value of such models will continue to remain dependent on continued advancement of experimental test methodologies using PMHS and dummies [7]. Cadaver tests are useful in that they provide for a means to study injuries resulting from a known set of vehicle, crash and pedestrian parameters. However, since PMHS are imperfect models of real humans, in-depth crash analyses provide a means to examine actual injury incidence to pedestrians. However, since the cases are retrospective analyses, errors in vehicle speed, pedestrian orientation and pedestrian impact location predictions can misguide mechanistic descriptions of injuries. Thus a combination of PMHS tests and retrospective analysis provides for a more diverse approach to injury mechanism analysis.

In the current study, injury frequency, severity, source and mechanism of injuries sustained by 17 PMHS tested in full scale vehicle-pedestrian impact with five different vehicles are presented. To assist in interpretation of the results and to provide for a methodology to interpret the clinical relevance of the injuries, injuries sustained by 24 other PMHS from the literature and 67 pedestrians from a recent in-depth crash investigation study were used.

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The Crash Injury Research and Engineering Network (CIREN) was initiated in response to a recommendation made by the National Academy of Sciences in 1985 to utilize a multidisciplinary approach to the study of crash injury, which provided the impetus for the concept of coordinated research by physicians, crash reconstructionists and engineers on the subject of injury. The CIREN program, which was initiated by the US National Highway Traffic Safety Administration in 1997, brings together experts from medicine, biomechanics, academia, industry and government to perform detailed analyses of the injuries sustained in specific collision modes. Individual crash cases are identified by CIREN centers and detailed information regarding the crash, vehicle and occupants is collected, organized and reviewed in depth by a team of experts with the goal of identifying the sources and mechanisms of the injuries sustained during the crash. While the CIREN program has typically focused on vehicle occupants, in 2002, the Honda INOVA Fairfax Hospital CIREN Center established a special program for crash investigations involving passenger cars or light trucks and pedestrians.

Between 2002 and 2007, 67 vehicle-pedestrian crash cases were admitted to the program. Details of the program, selection criteria and case evaluation methodology were published with some results in 2005 [29], and in 2007 some of the cases were combined with other databases to examine head impact characteristics [15]. But to date, no other studies have published data from the database; however, two additional studies are currently under review for publication [34] and [39]. Criteria for case enrollment included hospital admission with at least one AIS2+ injury, the pedestrian was oriented upright when struck by the front-end of a vehicle and the striking vehicle was a passenger sport-utility vehicle (SUV), minvan or small pickup truck. As a result of case selection criteria, higher severity vehicle-pedestrian crashes are over represented in the CIREN database and thus it cannot be used to determine statistically relevant population-based statistics about pedestrian crashes.

Once the pedestrian consents to the study, the pedestrian is interviewed, photographed, and measured (for anthropometric data). A crash reconstructionist works with the local police department to get consent from the vehicle owner, and then inspects, measures and photographs the vehicle and crash scene. Medical records from treatment and throughout the hospital stay are combined with pedestrian follow-up interviews at 6 months and 1 year to the other information to create each case file. When sufficient information was available, computational simulations of the crash were performed and parameter optimization was utilized to provide estimates of unknown crash parameters. Then the case is reviewed by a team of biomechanical engineers, trauma physicians and crash reconstructionists with the goal of identifying pedestrian kinematics and injury mechanisms. A confidence level is assigned to each injury mechanism and to the details of a crash summary provided by the team as the output of each case review. The current study presents some general information about the crashes, vehicles and injuries sustained by the pedestrians in the database, and then uses these to interpret the results of the PMHS tests.

II. METHODS

A. PMHS Tests

A total of 17 vehicle-pedestrian impact experiments with PMHS were performed [1],[3]-[9],[14],[15] (Table 1). The details of the test methods have been described previously so only a short summary is presented here.

Sled System: Drivable production versions [1],[3]-[9] or bodies in white [13]-[14] of each test vehicle were cut just rearward of the B-pillar, welded to a sled sub-frame, ballasted up to the vehicle's curb weight and attached to a carriage mounted to a deceleration sled system (Table A1). After each experiment, the vehicle was inspected for damage, and all damaged parts were replaced prior to each subsequent test. A small, light pedestrian sled that mimicked the vehicle's ground-reference-level was constructed and attached to the sled system to facilitate surrogate positioning prior to each test. The sled system's decelerator began decelerating the vehicle and pedestrian sled approximately 250 ms after initial vehicle-pedestrian contact at a constant 6g. An energy-absorbing catching mechanism was installed to catch the PMHS, prohibit ground contact and prevent additional injuries.

PMHS Preparation: Seventeen PMHS, all absent of pre-existing fractures, lesions or other bone pathology as confirmed by computed tomography (CT) scan, were selected for the studies. The PMHS were obtained and treated in accordance with the ethical guidelines established by the Human Usage Review Panel of the National Highway Traffic Safety Administration, and all testing and handling procedures were reviewed and approved by the CAB Biological Protocol Committee and an independent Oversight Committee at UVA. Each specimen was

TABLE 1. PMHS SUBJECT AND TEST INFORMATION.

PMHS ID	Ref.	Ref Test ID	Test Speed (km/h)	Vehicle	Struck Side	Limb Forward	Gender	Age (years)	Stature (cm)	Weight (kg)
1	[9][20][24][26]	1001	40	Small Sedan	Right	contralateral	F	61	173	81
2	[9][20][24][26]	1002	40	Small Sedan	Right	contralateral	M	70	170	54
3	[9][20][24][26]	1003	40	Small Sedan	Right	contralateral	M	62	175	82
4	[9][20][23][26]	1013	40	Large SUV	Right	contralateral	F	75	168	47
5	[9][20][23][26]	1014	40	Large SUV	Right	contralateral	M	75	170	57
6	[9][20][23][26]	1015	40	Large SUV	Right	contralateral	M	53	172	104
7	[21],[22],[25]	1064-S2	40	Mid-Sized Sed. 1	Right	contralateral	F	57	163	89
8	[21],[22],[25]	1065-T7	40	Mid-Sized Sed. 1	Right	contralateral	M	74	176	92
9	[21],[22],[25]	1066-S1	40	Mid-Sized Sed. 1	Right	contralateral	F	67	162	64
10	[21],[22],[25]	1067-S3	40	Mid-Sized Sed. 1	Right	contralateral	F	71	164	83
11	[21],[22],[25]	1068-T6	40	Mid-Sized Sed. 1	Right	contralateral	M	70	178	87
12	[21],[22],[25]	1069-M5	40	Mid-Sized Sed. 1	Right	contralateral	F	49	173	93
13	[21],[22],[25]	1070-M4	40	Mid-Sized Sed. 1	Right	contralateral	F	32	169	91
14	[46],[47]	1137	40	Mid-Sized Sed. 2	Right	contralateral	M	62	154	73
15	[46],[47]	1138	40	Mid-Sized Sed. 2	Right	contralateral	M	62	183	114
16	[46],[47]	1140	40	Small City Car	Right	contralateral	M	64	161	86
17	[46],[47]	1141	40	Small City Car	Right	contralateral	M	67	182	46
18	[14]	T1	25	Midsized Car C1	**	ipsilateral	M	54	180	75
19	[14]	T2	25	Midsized Car C1	**	ipsilateral	M	74	167	56
20	[14]	T3	32	Midsized Car C1	**	ipsilateral	M	48	170	62
21	[14]	T4	32	Midsized Car C1	**	ipsilateral	M	58	185	85
22	[14]	T5	32	C1 + Padding	**	ipsilateral	M	17	192	90
23	[14]	T6	32	C1 + Padding	**	ipsilateral	M	52	178	65
24	[14]	T7	32	C1 2x Bumper	**	ipsilateral	M	59	184	88
25	[14]	T8	32	C1 2x Bumper	**	ipsilateral	M	53	180	89
26	[14]	T9	39	Midsized Car C2	**	ipsilateral	M	68	175	88
27	[14]	T10	40	Midsized Car C2	**	ipsilateral	F	36	166	54
28	[41]	Y1	30	C3 (new)	Left	contralateral	M	70	167	68
29	[41]	Y2	40	C3 (new)	Left	contralateral	M	51	182	63
30	[41]	Y3	40	C3 (new)	Left	contralateral	M	66	177	84
31	[41]	T11	40	C1	Left	contralateral	M	53	167	72
32	[41]	T12	40	C1	Left	contralateral	M	78	170	68
33	[43]	T1	40	Sedan250*	Left	ipsilateral	F	52	160	50
34	[43]	T2	40	Sedan250*	Left	ipsilateral	F	76	166	74
35	[43]	T3	40	Sedan050*	Left	ipsilateral	M	32	177	75
36	[43]	T4	40	Van050*	Left	ipsilateral	M	78	180	64
37	[43]	T5	40	Van250*	Left	ipsilateral	M	76	172	60
38	[40]	HJ1	40	SUV	Left	ipsilateral	M	80	165	60
39	[40]	HJ2	40	SUV	Left	ipsilateral	M	84	185	85
40	[40]	HJ3	40	Minvan	Left	ipsilateral	M	80	171	80
41	[40]	HJ4	40	Minvan	Left	ipsilateral	M	70	171	61
							Mean	*61.9*	*172.7*	*74.6*
							St. Dev.	*14.7*	*8.1*	*15.9*

*-050/250 indicates the radius of the hood leading edge in mm

**-Not specified by the authors.

instrumented with kinematics and strain sensors, outfitted in tight fitting clothing, and fitted with a support strap under the arms and around the head. The support straps were attached to a solenoid release mechanism used to support the PMHS during pre-test positioning and release the PMHS prior to vehicle contact. Each PMHS was positioned with the right lateral side facing the vehicle and with the PMHS mid-coronal plane aligned approximately with the vehicle centerline. The lower extremities were positioned to mimic a mid-stance position with the right (struck side or ipsilateral) lower extremity positioned behind the body and the left lower extremity (contralateral) positioned in front of the body. The upper extremities of the surrogate were bound at the wrist, anterior to the body, with the left wrist closest to the abdomen, to ensure repeatable kinematics and to prevent the upper extremities from mitigating impacts to the pelvis, abdomen, thorax or head.

Test: The test event was initiated by a pneumatic propulsion system that accelerated the vehicle sled to approximately 40 km/h. The PMHS was released 20 ms prior to initial vehicle-pedestrian contact (usually at the bumper/lower extremity interface). After testing, all PMHS underwent a full body computed tomography (CT) scan, which was read and interpreted by a radiologist. Then a full body necropsy was performed by a team of orthopedic surgeons, pathologists' assistants and biomechanical engineers. All body regions were physically investigated for injuries and the radiology report was used only as a guide. Then the team produced a report detailing the presence and absence of injuries to all body regions, the results of manual laxity tests of the knees and ankles, and photos and/or drawings of each injury.

B. Additional Studies

To assist in interpreting the injuries sustained by the PMHS in the experiments, PMHS injuries sustained in other vehicle-pedestrian impact tests were reviewed. The literature contains several vehicle-pedestrian impact experiments with PMHS published in the 1970s and 1980s ([48], [5], [12], [18], [17], and several others). However, since the PMHS tests presented in this study involve late-model vehicles, only studies published after 1990 were considered for comparison in this study. Only one study was found from the 1990s [14] and three additional studies were published since 2000 [41], [43], and [40] (Table 1).

Study [14] presented the results of 10 vehicle-pedestrian impact experiments conducted with two different vehicles at speeds between 25 and 40 km/h. In four tests a standard vehicle ("medium-sized production car bod[y]") was used, in four tests the authors modified the bumper with padding or stiffeners to examine effects, and in the remaining two tests another vehicle was used with a modified bumper protrusion. Pedestrians were oriented laterally relative to the vehicle, along the vehicle centerline, in mid-stance gait with their struck-side limb forward. Subjects were supported by a steel cable that passed through a screw inserted in the skull of the PMHS and released 60 ms prior to impact. The authors do not mention whether or not the subjects were prevented from enduring a secondary impact with the ground after vehicle interaction.

Study [41] presented the results of five vehicle-pedestrian impact tests, three of which were performed with "a late model car cut-body" (C3 (new)) at 30 km/h (n=1) and 40 km/h (n=2). The other two tests were performed with "a car cut-body (C1) constructed before 1990) at 40 km/h. The PMHS were positioned laterally with respect to the vehicle, along the vehicle centerline, with their left sides facing the vehicle, in mid-stance gait with their struck-side limb rearward of the contralateral limb. The specific method of subject support was not described by the authors, but to say that the support mechanism was released 50 ms prior to vehicle contact. The PMHS were prevented from enduring a secondary (ground) impact via a "padded safety net"

[43] presented the results of five vehicle-pedestrian impact experiments using custom constructed "vehicle fronts" that possessed much simpler geometry than real vehicles, but had component stiffnesses that were similar to real vehicles. The vehicle geometries, termed "Sedan" and "Van", were based on those of multiple real vehicles with average model years of 1996 (sedan) and 1997 (van). The PMHS were positioned laterally with respect to the vehicle, along the vehicle centerline, with their left sides facing the vehicle, in the mid-stance phase of gait with ipsilateral limb positioned forward. The subject support method was not described by the authors, but subjects were released from their support mechanism 65 ms prior to initial vehicle contact. The subject's hands were bound at the wrist in front of the subject. The PMHS were permitted to sustain a secondary impact with the test facility floor.

Study [40] presented the results of four vehicle-pedestrian impact experiments using an SUV and a mini-van. While not explicitly stated, the vehicles appear to be cut bodies of late-model production vehicles. The PMHS were oriented laterally along the vehicle centerline, with their arms bound at the wrist anteriorly, their left sides facing the vehicle, and in mid-stance gait with the ipsilateral limp forward. Subjects were supported by a single steel wire that passed through a bone screw fixed to the skull that was released 60 ms prior to impact. The secondary impact was "mitigate[d]" by "cushioning material…set at and around the point of fall". The authors did not describe the deceleration of the vehicle after the impact.

All 24 PMHS underwent a physical necropsy to determine injuries sustained by the subjects; however, none of the studies described the detail with which the necropsies were performed, nor whether all or only some parts of the subject were investigated for injuries.

C. CIREN Pedestrian Database

The CIREN pedestrian database contains 67 vehicle-pedestrian crash cases involving impacts between a passenger car or light truck and a single pedestrian. The 67 pedestrians are composed of 16 females, 55 adults (18-79 years, mean: 44 years, SD.: 18 years) and 12 children (all male, 16 months to 17 years, mean: 11 years, SD: 5 years). The adults had average statures and weights of 169 cm (sd: 11 cm) and 76.5 kg (sd: 16.5 kg), respectively. The vehicles involved consisted of four pickup trucks, 43 sedans, five sports cars, 12 SUVs and three vans with an average model year of 1997 (range: 1986-2006, SD: 4.8 years) from 20 different makes with Nissan, Chevrolet, Honda, Toyota and Ford vehicles accounting for 42 of the 67 cases. Twenty nine of the crashes occurred during the daytime (06:00-18:00) and the other 38 occurred at night. 59 of the crashes occurred in dry/clear conditions with eight occurring in rainy/wet weather. Half (33) of the cases occurred on roads with speed limits between 72 and 89 km/h, 30% on roads with speed limits between 56-71 km/h, with the other 20% occurring on roads with speed limits 55 km/h or less. While all of the cases had speeds estimated by the investigating officer and the crash reconstructionist, 24 of the cases had sufficient information for speed, pedestrian position and pedestrian orientation estimation by computational optimization aimed at matching pedestrian contacts with vehicle contacts and final resting location of the pedestrian relative to the vehicle [29] and [33]. Half of the estimated impact speeds in these 24 cases were between 40 km/h and 55 km/h, with one case estimated to be below 40 km/h and 11 cases estimated to be 56 km/h or above. 17 of these 24 cases had vehicle impact speeds less than the speed limit, suggesting that vehicle braking prior to the impact occurred in these cases. All of the injuries sustained by the case pedestrians were coded using the 1998 version of the Abbreviated Injury Scale (AIS). For the current study, the injuries sustained by the pedestrians in the 67 cases were examined generally to understand how the population relates to the PMHS tests, and several specific cases were analyzed in detail for comparison with the PMHS tests.

III. RESULTS

A. PMHS Test Injuries

Some of the injuries sustained by subject numbers 1-17 (Table 1) have been examined in previous studies, but this is the first study to present a complete description of all of the injuries sustained (Table 2).

Head/Spine Injuries: Despite sustaining head impacts to the middle of the windscreen, the windscreen lower edge, the cowl and the hood at speeds between 7 and 15 m/s, only one subject sustained a skull fracture. The injury was a massive ring shaped fracture (with floating fragments) of the temporal bone, mandible, zygomatic arch, maxilla and orbital floor (Figure 1). Twelve of the 17 PMHS sustained cervical spine injuries ranging from mild to severe. Subjects 2, 7, 8, 9 and 13 sustained invertebral disc ruptures in the lower cervical spine with associated tearing of the anterior or posterior ligaments without fracture or facet dislocations. Subject 11 sustained a half-Jefferson fracture with associated comminution of the lateral mass with a Type III odontoid fracture and severe cord compression. Subject 1 sustained multiple disc ruptures with associated fractures of the lateral mass and lamina at C5. Subject 14 sustained bilateral dislocation of the facet joints at C6/C7 with associated ruptures of the anterior and posterior longitudinal ligaments, the ligamentum flavum and the interspinous ligaments and a fracture of the C6 spinous process. The PMHS also sustained injuries to the thoracic spine in 10 of the 12 cases and lumbar spine in 4 cases (not counting distal lumbar transverse process fractures). Again several of the thoracic spine injuries were disc rupture injuries with associated ligament tears (four occurred at the T11/T12 level), but several were severe including the fracture dislocation with complete spinal cord transection in Subject 4 (T6/7) and Subject 6 (T3/4). It should be noted that a failure of the release mechanism in subject 5 resulted in unrealistic injuries to the cervical and thoracic spines (see [9]). Also, Subject 16 sustained an injury at the C7/T1 level that is likely related to a pre-mortem surgical fusion of C3-C7.

TABLE 2A. PMHS INJURY DETAILS FROM THE CURRENT STUDY. SEE TABLE 2B FOR KEY.

							Ipsilateral Lower Extremity			Contralateral Lower Extremity		
PMHS ID	Head	Cervi. Spine	Thoracic	Lumbar/ Abdomen	Upper Extremity	Pelvis	Knee	Leg	Foot/ Ankle	Knee	Leg	Foot /Ankle
1		C3/C4 C4/C5 C5/C6 C5-LM	Ri-R10	L5-TP		Le IPR Ri IPR/SPR Ri Sac Bil SI		Prox Tib/Fib		LCL/ACL/PCL Lat Caps Pop		
2	Temp / Fcl	C5/C6	Bil R4-7 T10/T11				MCL/ACL Med Caps		OC Talus	ACL/LCL ACL Avul		
3			T4 IE,SE	L3-VB			ACL Fib Neck			ACL/LCL		
4		Odon C6/C7	n=34 R + St T6/T7 +Cord T11/T12 Ri-Lung, Dia	Liver		Bil IPR/SPR Bil SI Ri Ill, Sac PS	Med FemC MCL/ACL/PCL Lat Meni Pos/Med Caps		Med Mall	Med FemC LCL/ACL/PCL Lat Caps TibP Avul		Med/Lat Mall
5		**	**			Bil IPR/SPR Bil SI Ri Ill, Sac	MCL/ACL/PCL Pos/Med Caps		ATF ATF Avul Ant Caps	LCL/ACL/PCL Lat Caps TibP Avul		
6			T3/T4 T3/T4 T3-IE Ri-R4-7/10-12				MCL/ACL/PCL Med Meni Med Caps			ACL/LCL		ATF Avul
7		C5/C6		L1/L2		Ri IPR/SPR Ri SI Ri Ill, Sac PS	Med Laxity	Dist Tib/Fib		LCL		
8		C6/C7	T7/T8	T12/L1			Fib Head				Dist Tib/Fib	
9	Lac	C5/C6	Ri R6-8, Le R3-5	Liver L4 Ri, L5 Bil TP		Bil IPR/SPR Ri SI Ri Sac PS		Dist Tib/Fib		ACL Avul Lat Caps LCL LCL Avul	Dist Tib/Fib	
10		Odon C2-Comm	T5/T6 T6- VB/SP T11/T12 T12-SE n=15 R Bil	L4-Bil TP		Ri IPR/SPR Bil SI Ri Ill, Ri Sac	MCL/ACL	Dist Fib	Med Mall	ACL/LCL Lat Caps		
11		Odon C1/C2 C1-Jeff/LM C2-TP	n=18 R Bil T1/T2 T2/T3	T12/L1 T12-IE,Fac L1-SE		Bil SI Ri IPR Bil SPR Ri Ill, Ri Sac	Fib Head Med FemC ACL	Ri FemN* Dist Fib	Med Mall Post Mall Ant Caps	LCL/ACL/PCL Lat Caps Lat Caps		
12		C5 Fac		L4/L5-Bil TP		Ri Ill Ri Ischium Ri Acet Ri IPR	ACL	Dist Tib/Fib		ACL/LCL Lat Caps		
13		C4/C5		L4 Le, L5 Bil TP		Ri IPR/SPR Ri SI Sac	Med Caps MCL			ACL/LCL Lat Caps Lat Caps		
14		C6/C7 C6 C6/C7-BFD	Le R6 T12-SE T11/T12	Spleen		Bil IPR/SPR Ri SI Ri Sac Ri Acet	MCL/ACL OC Avul Med/Lat TibP			Lat Caps		
15			n=9 R + St T11/T12		Le Scap	Ri Acet/IPR Ri Sac				LCL Avul Fib Head Lat Caps		ATF Avul
16		C7/T1$^{\%}$ C7/T1$^{\%}$	n=17 R				MCL					
17			n=12 R	Bil L2-L4 TP	Ri Scap	Bil IPR/SPR Bil SI Sac	Prox Tib Fib Neck MCL Avul	Dist Fib		Med TibP LCL Avul		

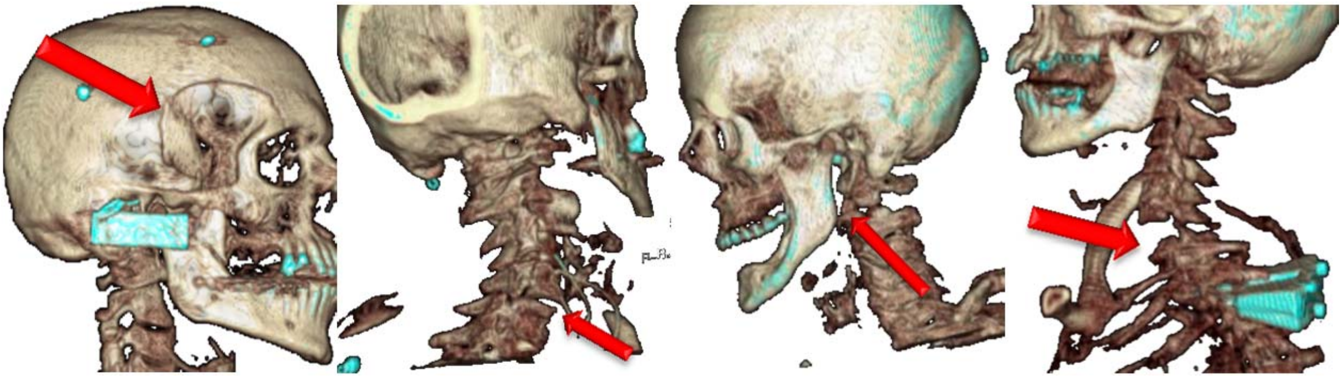
TABLE 2B. PMHS INJURY DETAILS FROM PREVIOUS STUDIES. KEY APPLIES TO TABLES 2A AND 2B.

							Ipsilateral Lower Extremity			Contralateral Lower Extremity		
PMHS ID	Head	Cervical Spine	Thoracic	Lumbar/ Abdomen	Upper Extremity	Pelvis	Knee	Leg	Foot/ Ankle	Knee	Leg	Foot /Ankle
18												
19								Prox Fib				
20							Fib Head	Prox Tib				
21					Le Hum			Mid Tib Prox Tib				
22												
23		C7-IE						Prox Tib/Fib				
24		C5/C6										
25	Fcl											
26	Ri !						MCL/LCL ACL/PCL Fib Head Lat TibC			Med TibP		
27							MCL Lat Men					
28	Temp/Fcl			L1 VB				Mid Tib Prox Tib/Fib				
29	Temp	C6-VB					ACL/PCL					
30					LE Elbow			Prox Tib/Fib				
31								Prox Tib/Fib			Prox Tib/Fib	
32		C7/T1			Le Clav Le Glen			Prox Tib/Fib			Prox Tib/Fib	
33												
34								!				
35						Ramus!		!				
36	!	C7!				Ramus/Acet!		!				
37		C7!				Ramus/Acet!		!				
38	Abras				Le Forearm	Le SPR/IPR	MCL Avul Post/Med Caps					
39	Cont		R5/R6		Le Forearm	SPR/IPR!	MCL/ACL Avul MCL					
40	!		R5/R6			Le SPR/IPR	Fib Head	Tib/Fib!				
41	!		R11/R12				MCL/ACL Avul MCL					CF

!-No additional information was provided
*The only thigh injury observed in any test
**Release failure caused unrealistic injuries
%-C3-C7 were fused surgically

COLOR CODES
Organ-Thorax/Abdomen
Soft Tissue-Ligament, Tendon Meniscus, Disc
Superficial-Abrasion, Contusion, Laceration
Bone-Fracture, Dislocation

Abras-Abrasion
Acet-Acetabulum
ATF-Anterior Talofibular Ligament
Avul-Avulsion
Bil-Bilateral
BFD-bilateral facet disclocation
Caps-Capsular Ligament
CF-Calcaneofibular Ligament
Clav-Clavicle Scap-Scapula
Comm-Comminuted
Cont-Contusion
Dia-Diaphragm
Dist-Distal
Fac-Facet
Fcl-Facial
FemC-Femoral Condyle
Fem-Femur
FemN-Femoral Neck
Fib-Fibula[r]
Fib-Fibula
Glen-Glenoid Cavity
Hum-Humerus
IE-Inferior Endplate
Ill-Illiac Wing
IPR-Inferior Pubic Ramus
Le-Left
LM-Lateral Mass
Mall-Malleolus, Mid-Middle
Med-Medial
OC-Osteochondral
Pop-Popliteus Muscle
Pos-Posterior
Prox-Proximal
PS-Pubic Symphysis
Ri-Right
R-Rib
Sac-Sacrum
SE-Superior Endplate
SI-Sacro-Illiac Joint
SPR-Superior Pubic Ramus
SP-Spinous Process
St-Sternum
Temp-Temporal
TibP-Tibial Plateau
Tib-Tibia
TP-Transverse Process
VB-vertebral body



Subject 2 *Subject 2* *Subject 10* *Subject 14*

Figure 1. Head and neck injuries. Subject 2: a massive depressed skull fracture (left), and an intervertebral disc and associated anterior longitudinal ligament (ALL) rupture at C5/C6; Subject 10: type III odontoid fracture with associated comminution of C2; Subject 14: bilateral facet dislocation with multiple ligament ruptures at C6/C7 with an associated fracture of the C6 spinous process.

Thorax and Pelvis Injuries: Ten of the PMHS sustained rib fractures with six subjects sustaining 9 or more fractures. Fractures were generally dispersed including anterior and posterior fractures (sometimes of the same rib) and fractures on both the struck and contralateral sides. Likely as a result of the 34 rib fractures sustained by subject 4, lacerations of the right lung and diaphragm were also observed. Other than those, only three other thoraco-abdominal organ injuries occurred: liver lacerations in subjects 4 and 9 and a spleen laceration in subject 14. Twelve of the PMHS sustained injuries to the pelvis, with most of the injuries involving multiple fractures of pubic rami, iliac wing, acetabulum and sacrum with sacro iliac and pubic symphysis disruption. While the most extensive pelvic injuries occurred in the tests with the SUV, severe pelvic injuries occurred in tests with all five vehicles (Figure 2).

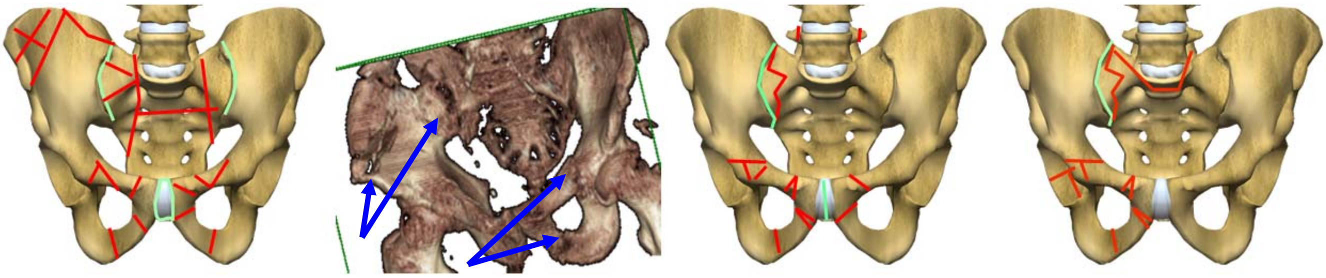

Subject 4 *Subject 5* *Subject 9* *Subject 14*

Figure 2. Diagrammatic descriptions and a 3-D CT reconstruction of pelvic injuries test specimens. Fractures are shown in red and ligamentous (joint) ruptures are shown in green.

Lower Extremity Injuries: All but one of the subjects sustained at least one lower extremity fracture (Figure 3) or ligament rupture on the struck side lower extremity. Subject 15 did not sustain any injuries to the ipsilateral lower extremity and Subject 8 sustained only a crush fracture of the fibula (which is the result of direct contact with the vehicle bumper). In most of the cases, the struck side lower extremity was injured by a fracture to the tibia/fibula or a fracture or ligament rupture of the knee joint, but not both. The data suggest that once the knee or leg sustains an injury, the corresponding leg or knee is not subjected to injurious loading. Three of the four exceptions to this tenet occurred in cases with mid-sized sedan 1, which had a protruding lower stiffener at approximately 250 mm above the ground, where subjects sustained a distal fracture of the tibia/fibula (occurred in 5 of 7 cases) in conjunction with knee injury. While there were a few femoral condyle fractures, only one thigh fracture occurred to the ipsilateral femoral neck of Subject 12. On the contralateral side, knee injuries occurred in 15 of the 17 cases and with leg fractures in only two of the cases. Knee injuries tended to be severe in nature involving rupture of cruciate ligaments and the medial collateral ligament (MCL) and medial capsule (ipsilateral side) or the lateral collateral ligament (LCL) and lateral capsule (contralateral side). Additionally, fractures of the knee joint occurred in 13 of the 34 knees, including both avulsion fractures and fractures of the femoral condyles or tibial plateaus. Only two of the 34 lower extremities did not sustain injuries to the knee joint or leg. Ankle injuries occurred in five cases on the ipsilateral side and three cases on the contralateral side.

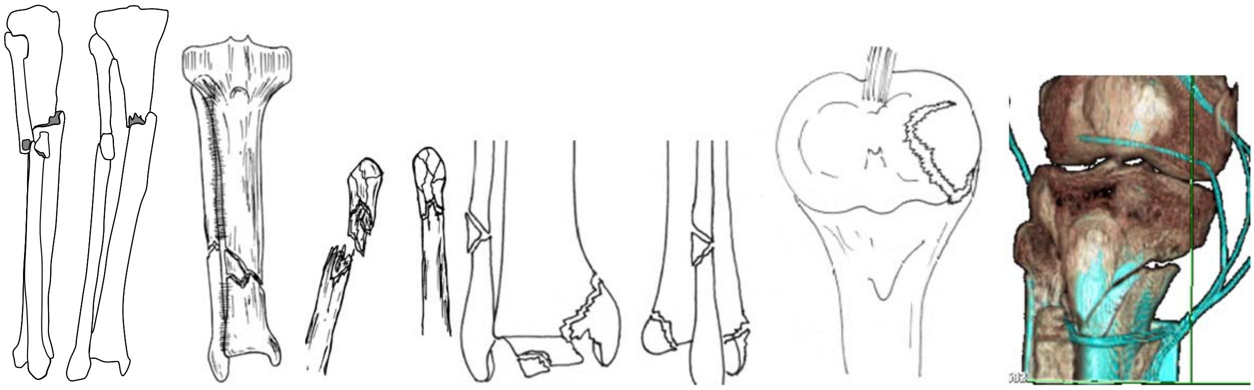

Subject 1 *Subject 7* *Subject 8* *Subject 11* *Subject 13* *Subject 17*

Figure 3. Examples of lower extremity fractures seen. Subject 1: proximal tibia/fibula fracture with a fibular wedge; Subject 7: distal tibia fibula fracture with tibial comminution; Subject 8: a crush fracture of the fibular head and neck; Subject 11: medial and posterior malleolar fracture with fibular wedge; Subject 13: osteochondral avulsion fracture of the tibial plateau (capsular ligaments); Subject 17: oblique fracture of the

proximal tibia and MCL avulsion fracture of the medial femoral condyle.

B. PMHS Test Injuries from Previous Studies

Overall, there were substantially fewer spinal, thoracic and pelvic injuries reported in the previous studies than in the current study, and the injuries reported in the previous studies were much less severe (Table 3).

Table 3. Injury frequency comparison between current and previous studies. Numbers indicate cases (or subjects, or tests) unless otherwise indicated.

		Head	Cervical Spine	Thorax/ Abdomen		Pelvis	Lower Extremity	
	n	Frac. /Superficial	Frac. /Soft Tissue /Both	Rib Frac. /Frac. Subjects	Organ	Frac. /soft tissue/ both	Ipsilateral: Leg/Knee/ Both	Contralateral: Leg/Knee/ Both
Current Study	17	1/1	2/5/5	Many/10	3	2/0/10	2/9/5	1/14/1
Previous Studies	24	3/5	4/2	6/3	0	6/0/0	13/8/2	2/1/0

Head/Spine Injuries: In three of the 24 test subjects included, the subjects sustained skull fractures, and superficial injuries were reported in five other cases. Only two subjects sustained soft tissue injuries (one disc rupture at C7/T1 and one ligament rupture at C5/C6) to the cervical spine and four of the subjects sustained fractures including an endplate fracture of C7, a vertebral body fracture of C6 and two non-specific fractures of C7. Only one other spinal injury (a vertebral body fracture L1) was reported in the previous studies.

Thorax and Pelvic Injuries: Of the 24 subjects tested, only fractures to 6 ribs were reported to three specimens described by [40]. No thoracoabdominal organ injuries were reported in the 24 previous tests. Pelvic injuries were only reported by two of the authors [43] and [40] with pubic ramus and acetabular fractures reported in three tests by [43] and pubic ramus fractures reported in three of the four cases from [40]. No studies described rupture of the sacroiliac ligaments or pubic symphysis, and no iliac wing or sacral fractures were reported.

Lower Extremity Injuries: The previous studies reported almost as many lower extremity injuries on the ipsilateral side as in the current study; however, five of the 24 subjects sustained no ipsilateral lower extremity injuries, including four of the 10 tests reported by [14]. All four of these tests were performed at lower speeds (25 and 32 km/h) than in the current study. Relative to the current study, there was a greater proportion of ipsilateral leg fractures compared to knee injuries in the previous studies with 13 of the 24 subjects sustaining leg fractures and with only eight subjects sustaining knee injuries. Like the current study, however, it appears that only two of the 24 subjects sustained a knee injury in addition to a leg fracture, and in the two cases the knee injuries are not related to bending or shearing, but are simply direct contact injuries to the fibular head. The types of knee injuries and leg fractures in the previous and current studies are similar. Only four contralateral lower extremity injuries were found in the previous studies.

Upper Extremity Injuries: Lastly, while two scapula fractures were reported in the current study, the previous studies included one humerus fracture, one fracture of the glenoid, one clavicle fracture and three superficial injuries.

C. CIREN Summary Data

Eleven of the 67 pedestrians in the CIREN study sustained fatal injuries as a result of the vehicle impact. Two of the pedestrians sustained the maximum AIS (MAIS) severity of 2, 34 (53%) had MAIS 3, 16 (24%) had MAIS 4, 14 (21%) had MAIS 5, and 1 had MAIS 6. Injury severity scores (ISS) ranged from 9 to 50, with one 75, and 36% of the scores were above 30. The 67 pedestrians in the CIREN database sustained 159 head injuries (82 AIS3+), 56 thorax injuries (36 AIS3+), 36 abdominal injuries (15 AIS3+), 34 spine injuries (8 AIS3), 134 upper extremity injuries (23 AIS3), and 269 pelvis and lower extremity injuries (77 AIS3+) (Figure 4). As a result of the injuries sustained, the pedestrians spent between 2 and 112 days in the hospital (mean 17.4 days, SD: 21 days) and between 0 and 44 days in the intensive care unit resulting in hospital charges between $8,000-$385,000 (USD).

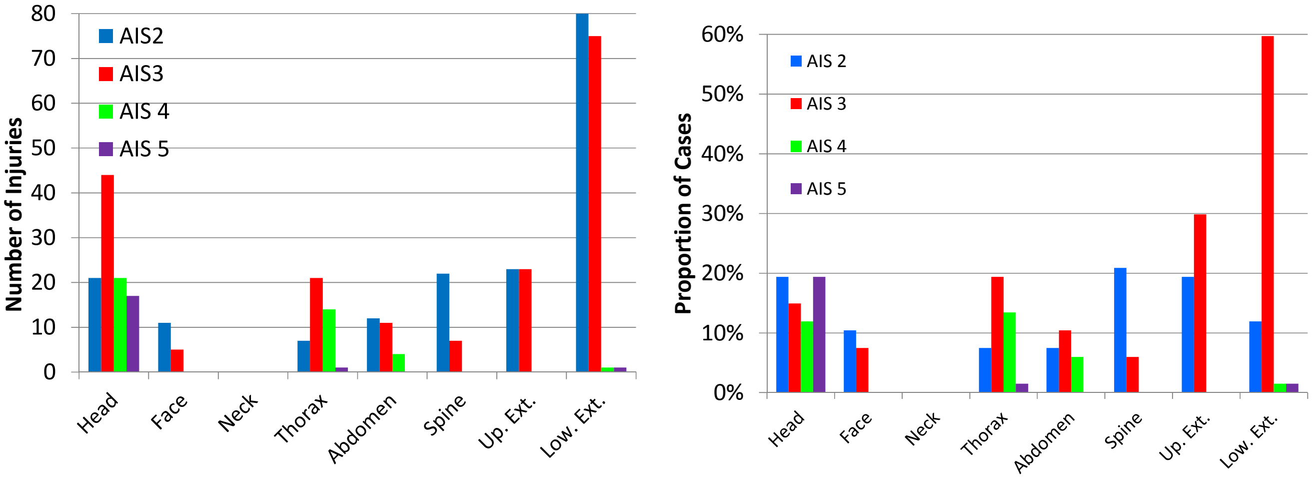


Figure 4. Number of injuries in the CIREN database by AIS level and AIS body region (left) and severity of injuries by proportion of cases (right), where each bar describes the proportion of cases in which the most severe injury to that body region was of the indicated AIS level.

Head, Thorax and Abdomen Injuries: Thirty-one of the 67 pedestrians sustained the 82 AIS3+ head injuries, which included 15 AIS 5 injuries, five of which were diffuse axonal injury, 13 instances of subdural hematoma, 20 subarachnoid hemorrhages and 14 skull fractures (Figure 4). There were 23 facial fractures, 16 of which were AIS 2+ including five AIS 3 orbital blow-out fractures (one pedestrian had two of these injuries). 56 total thoracic injuries were sustained by 34 pedestrians with 23 pedestrians sustaining AIS 3+ injuries including 1 AIS 5 injury (10 rib fractures with bilateral hemothoraces). Common injuries included rib fractures, pulmonary contusions and pneumothoraces, with one subject sustaining a minor (AIS 4) aortic rupture and one pedestrian sustaining a tear of the intimal layer of the aorta. Abdominal injuries were less common with 22 pedestrians (16 AIS 2+, 11 AIS 3+) sustaining 36 total injuries including 7 splenic, 6 liver and 3 kidney lacerations.

Spine Injuries: 21 pedestrians sustained spinal injuries, with 4 pedestrians sustaining AIS 3 injuries and one with an AIS 6. The AIS 3 cases included one with epidural hematomas at both C5-C7 and T1-T2, one with a teardrop fracture with associated facet and pedicle fractures at T7/T8, one with a C5 pedicle fracture and one with a C2 lateral mass fracture. The AIS 6 injury was an atlanto-occipital (AO) dislocation with associated fractures of C1 and C2. Of the 34 spinal injuries, 6 were cervical spine injuries, 16 were thoracic spine injuries (vertebral body, endplate, spinous process, pedicle, facet and transverse process fractures), and 12 were lumbar spine injuries (vertebral body, endplate and transverse process fractures).

Upper, Lower Extremity and Pelvis: The 134 upper extremity injuries were sustained by 53 of the 67 pedestrians, including 20 cases with AIS 3 injuries. 85 of the injuries were AIS1 superficial injuries, and there were 12 clavicle fractures, 17 humerus fractures, 6 scapula fractures two radius fractures, one ulna fracture and two radius/ulna fractures. (all forearm fractures were AIS 3). Pedestrians in all but six of the cases (n=61) sustained pelvis or lower extremity injuries with 42 pedestrians (60% of cases) incurring AIS 3+ injuries, one with an AIS 4 and one with an AIS 5 (both open book pelvic fractures). Of the 269 injuries, 110 were AIS 1 or 2 superficial injuries, and there were 7 knee ligament injuries, 37 fibula fractures, 7 ankle fractures, 6 femur fractures, 47 pelvic injuries, 31 tibial shaft fractures, and 12 tibial plateau fractures. 19 of the pedestrians sustained the 47 pelvic injuries including seven acetabulum fractures, five iliac wing fractures, 16 pubic rami fractures, seven sacrum fractures, three SI joint injuries and one injury to the pubic symphysis.

IV. DISCUSSION

Injury Frequency: The PMHS test data showed a similar distribution of musculoskeletal injuries as in the CIREN cases with all 31 PMHS sustaining at least one AIS 2+ lower extremity injury, rib fractures occurring in more than half of the tests, and skull fractures occurring in five tests. Overall, and on a per subject basis, there were far more injuries sustained by the PMHS in the current study than in the previous studies. While three subjects from the previous studies did not incur any injuries, two of these were tested at a speed 20% lower than in the current study (32 km/h). The average age of the subjects used in the current study (63) is similar to the average age of the subjects in the previous studies (61) and the subjects in both the current and previous studies had widely varied bone mineral density. However variations in bone strength or test speed do not appear to be sufficient to explain the difference in numbers of injuries between the two sets of tests. One possibility for the difference in injuries reported is that additional injuries occurred in the previous studies and they were either not found during necropsy or not reported in the studies. For instance, only one thoracic or lumbar spine injury was reported for the 24 tests from the previous literature, whereas only 6 specimens in the current study did not sustain lumbar or thoracic spine injuries (not counting fractures of the transverse processes). In the current study, many of the thoracic and vertebral spine injuries were identified by the pre-necropsy CT scan, but the remaining injuries were identified as a result of the detailed necropsies. Additionally, it is not clear whether or not [43] investigated the presence of injuries to the contralateral lower extremity (none were reported) since the authors reported "diagnostic radiographs were made of the struck-side femur, tibia/fibula, knee joint, hip joint and pelvis", and that the subject was "autopsied…and impact-related injuries were catalogued".

Head Injuries: In addition to the differences between the two sets of PMHS injuries, there were some differences between the injuries sustained by the PMHS and the pedestrians from the CIREN study. The CIREN database, like other databases and epidemiological studies of pedestrian injury distribution, shows that head injuries are the most severe injury sustained by pedestrians during vehicle impact: pedestrians in 31% of the cases sustained AIS 4+ head injuries and AIS 5 head injuries were sustained in 19% of the cases. While the majority of head injuries, and all of the most severe head injuries, were brain injuries, and since brain injuries normally cannot be detected in PMHS, PMHS can only be used to investigate skull fractures. While all of the PMHS were tested in the same conditions (lateral impact, vehicle centerline) and the CIREN impact conditions varied widely, a similar proportion of skull fractures were seen in the PMHS tests (9.8%) as in the CIREN study (13.4%). While in the CIREN cases the skull fractures could have occurred as a result of impact with the ground (secondary impact) after the vehicle crash, head impacts in the cases where skull fracture occurred were sourced to windscreen (n=3), the A-pillar (n=3) the cowl, the hood and the right side mirror. The PMHS with skull fractures sustained head impacts to the cowl/lower windshield/rear hood area in both the [14] and [40] studies, and Subject 2 (from the current study) sustained head impact to the lower third of the windshield with possible contact with the instrument panel. It is not surprising that Subject 2 sustained a skull fracture since it had the highest impact velocity of all 17 PMHS (14.5 m/s), and had a head injury criteria (HIC15) that was second highest of all PMHS (3647, Subject 4 had HIC = 3694). It is surprising however that other PMHS did not sustain skull fractures since many had similar impacts to the instrument panel after penetrating the windscreen, and 8 subjects without fracture sustained HIC15 values above 1000.

Spine Injuries: The biggest discrepancy between injuries sustained by the PMHS and the CIREN pedestrians was in injuries to the spine. Only five of the 67 CIREN subjects sustained AIS3+ injuries to any region of the spine, whereas six of the 17 PMHS sustained cervical spine fractures that would be classified as AIS3+ and five additional subjects sustained disc ruptures with associated ligamentous damage that would have been given AIS3+ codings with concomitant nerve root or cord damage. While it was not possible in all cases, the mechanism of cervical spine injury in the PMHS was investigated by comparing the injury and other case information to injuries produced in controlled loading experiments of PMHS (similar to the methods employed by [11]. For instance, the type-III odontoid fracture sustained by subject 4 was likely due to local shearing which could have resulted from global extension [32] or global compression with some lateral loading [2]. However, this subject also sustained a rupture of the ALL at C6/C7 suggesting that the global extension/distraction mechanism is most likely.

One potential source for extension of the neck is in how the subjects were supported and held prior to the crash: one support strap under the arms and across the back designed to support the majority of the weight, and another strap designed to support and position the head neutrally. It is possible that too much weight was supported by head strap which may have resulted in sufficient extension for the injury. However, both [14] and [40] supported the entire weight of subjects by means of a single support bolted to the skull of the PMHS and only two (of 14) subjects were reported to have cervical spine injuries (insufficient information was provided to determine injury mechanism). Furthermore, disc ruptures with associated ALL ruptures (suggesting extension/distraction) occurred in subjects 7, 8, and 13; in Subjects 2, and 9 disc and ALL ruptures were coupled with posterior longitudinal ligament (PLL) ruptures in the absence of spinous process fractures suggesting distraction was the injury mechanism [42]. Video images indicate that a whipping motion of the head/neck occurred in most of the subjects after initial bumper/lower extremity contact and before head contact that resulted in relatively large magnitude neck tension/extension. Study [41] examined spinal elongation through video analysis and showed that in the case of a C6 vertebral body fracture, the subject sustained a relatively high elongation of the cervical spine. It is not clear from the description of what the mechanism was, but vertebral body fractures (the “teardrop” ALL avulsion types) can result from extension with or without associated tension [32]. The absence of similar injuries in the CIREN pedestrians suggests that such severe extension or tension is restricted from becoming injurious by the active musculature that is absent in PMHS.

Subjects 1, 10, 11, 12, and 14 had injuries that suggested global compression mechanisms: subjects 1 and 12 had injuries to the C5 vertebra (lateral mass fracture and inferior fact fracture), subjects 10 and 11 had odontoid fractures without other injuries (10) or with a Jefferson fracture (11), and subject 14 had a bilateral facet dislocation at C6/C7 [2], [1], [35], [32]. Examination of the video images (Figure 5) showed that compression can occur during head-to-vehicle impact. In the case of subject 14, shoulder impact to the hood deformed the hood significantly in advance of the head impact, and when the head hit the vehicle, the shape of the deformed hood surface where the head hit resulted in the top of the head being loaded by the hood. Since the PMHS continued to slide up the vehicle after head contact, the neck visibly buckled under this compressive loading. A similar effect occurred in subject 12 when the head struck the lower edge of the windscreen and cowl, and its motion (relative to the vehicle) stopped almost immediately as the thorax continued to slide up the vehicle placing the neck in compression. In three out of the six CIREN cases where cervical spine injuries occurred, the injuries sustained suggested that compression was either a contributing factor or a possible injury mechanism (C1 lateral mass fracture, C2 lateral mass fracture and C5 pedicle fracture).

Figure 5. Video images from two tests where axial compressive loading was applied to the spine. The red line estimates the orientation of the spine in subject 14, the green arrow estimates the direction of the reaction force applied by the vehicle to the head at contact and the orange arrow shows the direction of motion of the thorax after contact due to sliding.

Thoracic Injuries: Numerous other studies have discussed thoracic injury risks to pedestrians ([28], [16], [30], [44], and others), and data from the PMHS tests and the CIREN study further highlight the risks of injury to the thorax of pedestrians. There were far more rib fractures reported in the current study than in the previous PMHS tests. In fact, only [40] reported any rib fractures, while rib fractures were produced with every vehicle used in the current study. Given this discrepancy, it seems likely that rib fractures were not reported in the other studies because the post-test injury assessments performed did not specifically target a search for rib fractures. Previous research has shown that rib fractures are under identified by radiologists from both plain-film X-ray and CT scans and that they are best found when a detailed examination of every rib is performed during autopsy/necropsy [8], [19], [27], and [36]. Despite the difficulty in identifying rib fractures using radiography, 19 of the 67 pedestrians in the CIREN study had at least one rib fracture, and rib fractures accounted for 20 of the 56 thoracic injuries.

Pelvic Injuries: While in most retrospective examinations of pedestrian injuries, pelvic injuries are coupled with lower extremity injuries, several studies have examined pelvic injuries separately from other lower extremity injuries. [37] showed that 12.2% of pedestrian injuries in the German In-Depth Accident Study were pelvic fractures and [13] found them to account for 6% of injuries to hospitalized pedestrians in a US hospital database. Reference [6] coupled them with lower extremity injuries but did mention that pelvic fractures were the 5th most common AIS2+ injury to pedestrians in the Pedestrian Crash Data Study database. However, pedestrians in the CIREN database sustained pelvic injuries more frequently than reported in other studies: pelvic injuries were 31% (n=48 out of 157) of all AIS2+ lower extremity injuries and AIS2+ pelvic injuries occurred in 23 of the 50 pedestrians sustaining AIS 2+ lower extremity injuries. This discrepancy is likely the result of the oversampling of severe cases in CIREN studies, which results from the case selection criteria. Despite oversampling of severe cases, pelvic fractures in the current PMHS study were more frequent and more severe than in both the previous PMHS tests and the CIREN pedestrians. Massive pelvic fractures and/or joint disruptions were produced in 12 of the 17 subjects using all five vehicles in the study. In the previous studies, no pelvic fractures were reported in any of the PMHS from the [41] and the [14] studies. However, in 6 of the 9 other specimens, pubic rami and acetabular fractures were reported. Using the pelvic fracture classification of [49] and [3], the fractures seen in the current study, referred to as “open book” due to the absence of a stable connection between the right and left innominate bones, are termed LC-3 for lateral compression of the highest severity. While such fractures have been associated with a 50% mortality rate, only a 3.6 % incidence has been reported among pedestrians struck by vehicles [10], suggesting that the fractures seen in the current study are rather rare in the field data.

There are two reasons why pelvic injuries in the current study were more frequent and more severe than in the CIREN database. First, the average age of subjects in the current study was 63 years, whereas the average age of subjects in CIREN was 38 years. The incidence of pelvic injury has been shown to increase as a function of age with steep increases occurring after age 60 (e.g. [38]). Second, the test conditions in the current study aimed to orient the mid-sagittal plane of the pelvis of each specimen perpendicular to the direction of vehicle motion, which may be the most severe condition for pelvic loading. When the pelvis is slightly oblique relative to the vehicle, the force vector applied to the pelvis at contact may not pass through the center of gravity of the pelvis and thus some of the force may go to rotate rather than compress (and accelerate) the pelvis. This is another reason why pelvic injuries were not reported (produced) in the studies by [41] and [14]. In those studies, the authors do not explicitly state whether or not the thorax or pelvis was oriented identically perpendicular to vehicle motion or whether a slight rotation was present, and hand-drawn images from the study suggest that some rotation might have been present.

Lower Extremity Injuries: PMHS in the current study sustained a high frequency of knee injury (29 of the 34 knees were injured) and relatively low frequency of leg fractures (7 of the 34 legs) compared to CIREN where of the 39 pedestrians sustaining AIS2+ leg or knee injuries, there were 11 injured knees and 38 injured legs. Similar to the current study, only one of the 78 limbs sustained both a knee injury (tibial plateau fracture) and a leg fracture (tibia shaft), but this case was abnormal in that the pedestrian was missing sections of both fibulas either from previous surgeries or a congenital condition. One possible explanation for the discrepancy in the incidence of knee injuries vs. leg fractures is that the muscular support of the knee joint in walking/running/standing pedestrians may provide increased support of the joint and increase its bending stiffness enough to result in leg fracture prior to knee joint injury. Such muscular support has been previously investigated in volunteer studies [31] and in computational studies aimed at examining pedestrian response [45]. If this were the case for all PMHS, a similar distribution of leg and knee injuries would have occurred in the previous studies as well. However, the previous studies show a higher incidence of leg fracture and a lower incidence of knee injury, which suggest that the rotation of the knee joint may play a role: the study [14] does not provide extensive detail about pre-test orientation of the PMHS and hand-drawn images suggest that there might have been some rotation of the PMHS relative to the vehicle that may have resulted in the ipsilateral knee going into flexion under bumper loading rather than valgus bending.

Upper Extremity: Lastly, it should be mentioned that the only upper extremity injuries sustained by the PMHS in the current study were to the scapula (n=2 subjects), and upper extremity injuries were relatively common in the CIREN study. It is hypothesized that by binding the arms in front of the pedestrian, the upper extremities were protected from injury. This was done to prevent the ipsilateral upper extremity from getting pinned between the thorax and the vehicle which was shown to affect pedestrian impact kinematics [17]. It is hypothesized that upper extremity injuries in the CIREN cases occur either as a result of secondary (ground) impact or when the hand or elbow loads the vehicle hood prior to the thorax which could result in the relatively high number of clavicle and humerus fractures (see [39]).

V. CONCLUSIONS

All of the injuries sustained by 17 PMHS tested in full-scale vehicle-pedestrian impact were presented in the current study and two separate datasets were used to help understand the mechanisms and sources of the injuries as well as to examine their clinical relevance: 24 previous vehicle-pedestrian impact experiments and 67 vehicle-pedestrian impact cases from the CIREN pedestrian database. Skull fractures were relatively infrequent in both the PMHS tests and case studies, even with secondary (ground) impacts as a potential source in the case studies. The case studies, however, show numerous severe brain injuries as a result of vehicle or ground impact. There were more spinal injuries in the PMHS than in the case studies. The absence of musculature in the PMHS appears to subject PMHS to a greater risk of cervical spine injuries resulting from extension or tension than in the pedestrian case studies where such injuries were absent. However, both the PMHS and case studies depicted injuries that appeared to result from axial compressive loading, suggesting that these injuries are infrequent but clinically relevant. While pelvic injuries were common in the CIREN cases, pelvic injuries were more common and more severe in the PMHS tests. This is likely due to a combination of factors including the age/bone quality of the PMHS and that the PMHS were positioned to cause perfectly lateral loading from the vehicle whereas such conditions are probably rare in the field data. Data from both the PMHS tests and the case studies showed that knee injuries occurring with concomitant leg fractures, or leg fractures occurring with concomitant knee injuries, are rare occurrences and injuring the leg or knee appears to result in protection for the ipsilateral knee and leg.

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VII. APPENDIX

TABLE A1. VEHICLE GEOMETRY FROM THE PMHS TESTS.

Vehicle [Reference]	Bumper Height (mm)	Bumper Lead/ Protrusion (mm)	Hood Leading Edge Height (mm)	Hood Length (mm)	Hood Pitch (deg.)	Windshield Inclination (deg.)
Small Sedan [9],[20],[24],[26]	467	165	692	844	81	32
Large SUV [9],[20],[23],[26]	567	179	1019	825	81	36
Mid-Sized Sed. 1 [21],[22],[8]	527	162	782	928	83	58
Mid-Sized Sed. 2 [46],[47]	533	159	810	1129	83	31
Small City Car [46],[47]	669	43	813	363	64	42
C1 [14]	430	60	875	1200	82	41
C1 + Padding [14]	430	85	875	1200	82	41
C1 2x Bumper [14]	540	N/A	875	1200	82	41
C2 [14]	446	141	641	1110	80	45
C1 (old) [41]	383	145	763	1300	85	33
C3 (new) [41]	446	141	641	1110	80	35
Sedan [43]	500	140	740	N/A	79	N/A
Van [43]	580	160	860	N/A	65	N/A
SUV [40]	658	163	907	861	81	38
Mini-Van [40]	631	121	888	493	76	40