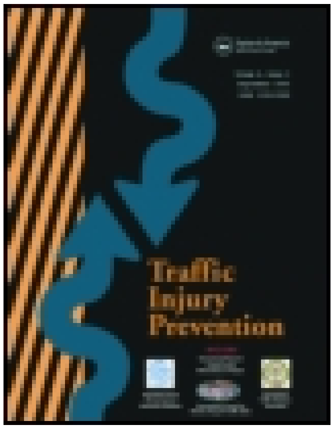

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A Review of Pelvic Fractures in Adult Pedestrians: Experimental Studies Involving PMHS Used to Determine Injury Criteria for Pedestrian Dummies and Component Test Procedures

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A Review of Pelvic Fractures in Adult Pedestrians: Experimental Studies Involving PMHS Used to Determine Injury Criteria for Pedestrian Dummies and Component Test Procedures

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Objectives: Perform a systematic review for the most relevant pelvic injury research involving PMHS. The review begins with an explanation of the pelvic anatomy and a general description of pelvic fracture patterns followed by the particular case of pelvic fractures sustained in pedestrian-vehicle collisions. Field data documenting the vehicle, crash, and human risk factors for pedestrian pelvic injuries are assessed.

Method: A summary of full-scale PMHS tests and subsystem lateral pelvic tests is provided with an interpretation of the most significant findings for the most relevant studies.

Conclusions: Based on the mechanisms of pedestrian pelvic injury, force, acceleration, and velocity and compression have been assessed as predictive variables by researchers although no consensus criterion exists.

Keywords: pelvis fractures, pedestrian crashes, PMHS

Pelvic Anatomy

The pelvis represents the link between the axial skeleton and the major weight-bearing structures of the lower extremities. It is composed of 3 major bones—the ilium, the ischium, and the pubis—that fuse at the acetabulum and form a socket for the head of the femur (Figure 1). The rounded head of the femur articulates with the acetabulum and is held within the socket by ligaments. Laterally, the proximal femur exhibits a large bony prominence, the greater trochanter, for the attachment of muscles. The ilium is situated superiorly and forms the broad upper lateral portion of the hip bone and the upper portion of the acetabulum. The top of the ilium has a curved edge commonly referred to as the iliac crest and an anterior prominence known as the anterior–superior iliac spine. The right and left ilium form the pelvic girdle and articulate with the sacrum posteriorly to form the sacroiliac (SI) joint. The postero-lateral bony pelvis is covered by multiple muscle layers, buttock fat, and skin. The ischium lies inferiorly and posteriorly. The superior and inferior rami join the pubis, which lies inferiorly and anteriorly. The anterior fusion of the right and left pubi forms a cartilaginous joint known as the symphysis pubis (PS).

In addition to the bony framework, the pelvic region houses several large vascular structures. The iliac arteries provide most of the blood supply to the pelvic wall and viscera. The lumbar and sacral arteries also lie in the pelvic cavity, as do the pelvic veins, which, for the most part, correspond to the arteries. Other vital structures within the pelvis include the reproductive organs, sigmoid colon, rectum, bladder, ureters, and urethra. Important nervous system structures that traverse the pelvis include the sacral plexus and the femoral, sciatic, and obturator nerves.

Substantial differences are observed between male and female pelves. The female pelvis is smaller, wider, more oval, and tilted farther forward than the corresponding male pelvis. In addition, the bones of the male pelvis are thicker and heavier than those in the female pelvis. The superior aperture of the pelvis is larger in the female than in the male; it is more nearly circular, and its obliquity is greater; the sacrum is shorter and wider, and its upper part is less curved. The inferior aperture

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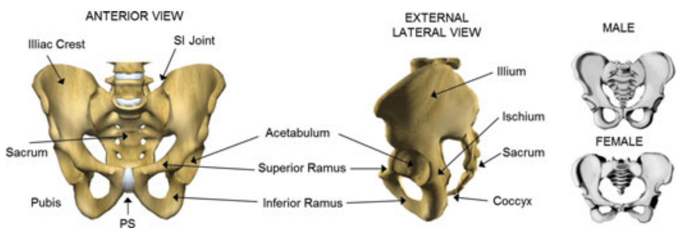

Fig. 1. Anatomical structures of the pelvis.

is larger and the coccyx more flexible. The sciatic notches are wider and shallower, and the spines of the ischia project less inward (Figure 1).

Pelvic Fractures—High Mortality

In general terms, the significance of pelvic injuries is highlighted by the fact that more patients die from pelvic fracture, and related complications, than from any other skeletal injury (Cryer and Johnson 1996). For pelvic fractures, the overall mortality rate in adults is approximately 10–15% (Flint and Cryer 2010; Rice 2007). Due to the high energy required to fracture the strong ring-like structure of the pelvis, injuries of the abdomen, chest, and head are often associated with pelvic fractures. In patients sustaining pelvic fractures with concomitant head injury, fractures of the pelvis may be initially overlooked and mortality rates for this population can approach 75 percent (Waddell and Drucker 1971).

Because injuries to the pelvic ring have significant consequences in terms of both death and disability, it is crucial to understand the injury mechanisms and to know the injury threshold, if the injuries are to be prevented. True single fractures in the pelvic ring are unusual injuries and typically occur in the elderly for minor falls. Although the PS and the SI joint will accommodate slight displacements, most impact forces create a minimum of 2 fractures in the pelvic ring. Associated with these fractures, significant loss of blood can occur from large blood vessels in the pelvic wall as well as from the fractured surfaces themselves. Disruption of the osseous pelvic ring leads to disruption of pelvic vascular structures (venous or arterial) in as many as 75% of patients (Thornton 2002). Overall mortality in patients with hemorrhagic shock and pelvic ring fractures after blunt trauma is approximately 40%. In the presence of an unstable fracture pattern, mortality increases to 52% (Eastridge et al. 2002). Open pelvic fractures lead to greater hemorrhage, increasing the risk of mortality to 70% (Dente et al 2005; Grotz et al. 2005; Perry 1980). In addition to the vascular injuries, serious injuries to the genitourinary system, the gastrointestinal system, and the lumbosacral plexus can lead to death or long-term disability.

Fast diagnosis of the presence of a pelvic bone fracture and determination of pelvic ring instability are important indicators, especially in the critical first hour of trauma care (Siegel et al. 1990). Morbidity and mortality are high and reported between 8.6% and 17% only for pelvic ring fractures and rise to 39% in patients with hypovolemic shock (Eastridge et al. 2002).

Pelvic Fractures—Pedestrian Epidemiologic Studies

The exact mechanism of pelvic injuries in pedestrian–vehicle crashes is not clearly understood; the pelvis is generally first loaded through the thigh when the vehicle impacts the pedestrian, posteriorly due to the pedestrian wrap around the vehicle; the pelvis is often directly loaded by the front-end or bonnet structures; and finally there is frequently direct contact to the ground/road surface.

One of the principal factors determining the frequency and severity of pedestrian pelvic fractures is the relative geometric relationship between the pedestrian and striking vehicle (Kerrigan et al. 2012; Longhitano et al. 2005). Though children are generally smaller than adults, the injury rate of pelvic fracture in vehicle–pedestrian crashes is similar for adults and children and ranges from 5% to 19% (Arregui-Dalmases et al. 2010; Derlet et al. 1989; Kong et al. 1996; O'Malley et al. 1985; Siram et al. 2011). This is presumably related to the distensibility of the pediatric pelvis without fracture when subjected to impact loading (Ouyang et al. 2003). Elderly adults, however, have a significantly higher incidence of pelvic fracture and nearly one-third of all elderly pedestrians struck by a motor vehicle sustain pelvic fractures (Kong et al. 1986; Siram et al. 2011). In particular, a higher incidence of pelvic fractures in elderly females is consistent with their postmenopausal reduction in injury tolerance and different geometry than males (Table 1; Ashton 1981, Stames et al. 2011). In addition to the increased fractured risk, mortality risk is increased in the elderly population subsequent to pelvic fracture, so bone quality another important factor to predict pelvic fracture. Impact speed was also associated with the incidence of Abbreviated Injury Scale (AIS) 2+ pelvis injury (Klinich and Schneider 2003); in the same study, the presence of thigh fracture was identified as a predictor for pelvis injury.

Ryan (1971) surveyed 713 patients with pelvic fracture dislocations and found that 154 of the 387 traffic-related fractures were to pedestrians. The most common pelvic fracture was that of the pubic ramus (305), followed by the acetabulum (89) and the ilium (79). There were a total of 116 dislocations divided equally among the hip, pubic symphysis, and SI joint.

Given the scenario of the front of the vehicle striking the lateral aspect of a pedestrian, the most common pattern of pedestrian pelvic fractures is lateral compression. Eastridge and Burgess (1997) examined 1014 pedestrians and found that 71.2% of pelvic fractures were lateral compression, 20.7% were

Table 1. Incidence of pelvic fractures as a function of age and sex

Age group ($n = 3641$) (years)[a]	Male (%)[a]	Female (%)[a]	Age group ($n = 6275$) (years)[b]	Male (%)[b]	Female (%)[b]
0–4	0	0	<15	5.3	8.2
5–9	2	3	15–55	12.7	21.0
10–14	1	2	55–65	12.3	28.5
15–29	1	3	>65	15.7	32.5
30–44	2	6			
45–59	5	6			
60–74	6	18			
75+	15	24			

[a]Ashton (1981).
[b]Stames et al. (2011).

anteroposterior, 5.4% were vertical shear, and 2.7% involved combined mechanical injury fractures. Depending on the area of the impact and the magnitude of the force, different lateral compression injuries are seen.

Young et al. (1986) categorized lateral compression fractures into 3 distinct types. Type I injuries involve a force directed posteriorly to the lateral aspect of the hemipelvis, which results in struck-side sacral buckle fractures or struck-side horizontal pubic rami fractures. If the force is applied to the posterior aspect of the pelvis, a more direct compression injury through the posterior half of the ilium and across the sacroiliac joint into the sacrum results and usually produces the classic lateral compression impaction fracture in the sacrum. Lateral forces directed anteriorly to the hemipelvis produce type II and III injuries. Type II injuries involve more internal rotation of the hemipelvis. This force tends to rotate the hemipelvis inward with the pivot point being the anterior SI joint. Consequently, the anterior portion of the sacrum is crushed and disruption of the posterior sacroiliac ligament complex may follow. As in type I injuries, struck-side sacral buckle and horizontal pubic rami fractures are associated with fracture of the struck-side iliac wing or disruption of the struck-side posterior SI joint. In type III injuries, the force continues from the struck-side across the midline to affect the non-struck-side hemipelvis. The struck-side hemipelvis sustains either a type I or II injury with associated internal rotation. This pattern has been described as a windswept pelvis because the contralateral pelvis undergoes external rotation. Contralateral vertical pubic rami fractures or disruption of the ligaments may occur. For the lateral compression fractures in the pedestrian study by Eastridge and Burgess (1997) 71% were type I, 24% were type II, and 5% were type III lateral compression fractures (Figure 2).

Edwards and Green (1999) found that an acetabular fracture results from loading the acetabulum through the femoral head following impact to the femur at the greater trochanter, and when the forces are distributed, a pubic rami facture often occurs simultaneously. They determined that 61.5% of the pedestrian pelvic fractures included fracture of the pubic rami of which 17.5% involved an acetabular injury.

In addition to loading direction, differences in load distribution, site of load application, and load magnitude appear to influence the location and severity of pelvic injuries. When forces are distributed, pubic rami fractures are the most common bony injury. Ashton (1981) provided a distribution of the fracture locations relative to the struck side (ipsilateral) and non-struck side (contralateral). He found that nearly 60% of all pedestrians with pelvic fractures sustained a pubic rami fracture on the struck-side aspect. He observed that the second most frequent injury was a fracture involving the pubic

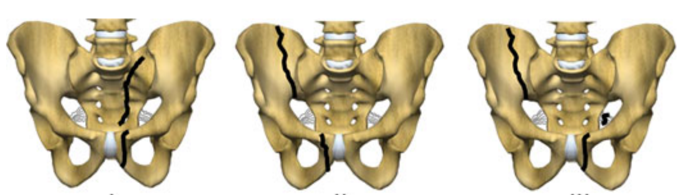

Fig. 2. Young et al.'s (1986) classification for lateral compression fractures.

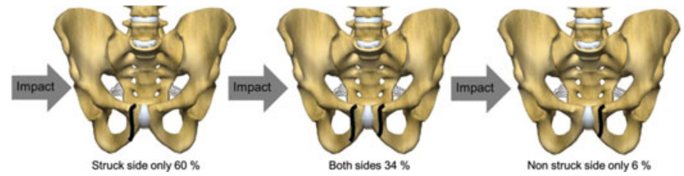

Fig. 3. Distribution of pelvic fractures relative to struck-side locations, based on Ashton (1981).

rami on both sides of the pelvis in 34% of the cases, and only 6% of the pedestrians with pelvic fractures sustained only non-struck-side fracture (Figure 3).

As indicated, fractures of the pubic rami do not necessarily occur on the same side of the pelvis as that impacted. In fact, a small percentage of the non-struck sides may be due to ground contact (Ashton 1981). However, non-struck-side fractures from either vehicle or ground contact are considerably less frequent than those on the struck side. For crashes at 20 to 40 km/h, pelvic fracture was 5 times more likely to be caused by primary contact with the vehicle rather than secondary contact with the road (Otte and Pohlemann 2001).

Injury Sources for Pedestrian Pelvic Injuries

Kam et al. (2005) analyzed the Pedestrian Crash Data Study and showed that 14 percent of pedestrians were impacted on anterior aspect of the body, 8% on the posterior aspect, 41% on their left side, 32% on their right side, and 5% unknown. When pedestrians struck on their left or right side were grouped, it could be seen that pedestrians struck laterally account for almost 74% of pedestrian collisions.

During impact of the pedestrian with a vehicle front end, the first contact is generally between the pedestrian's leg and the vehicle's bumper. This impact is typically followed by contact of the proximal lower limb or pelvis with the bonnet leading edge (BLE). During the impact sequence, however, the first contact between the bumper and legs can influence the angle and impact velocity of the second impact between the pelvis and the vehicle. Therefore, fracture of more distal anatomical structures of the lower limb can alter the likelihood of pelvic fracture by influencing the pedestrian kinematics although the precise correlations are not well understood. For example, pelvic fractures are more common in those aged 16 to 24 years in association with a tibial fracture but are less common in those aged over 60 with a tibia fracture (Edwards and Green 1999).

Vehicle design has demonstrated a strong influence on the likelihood of pedestrian pelvic injuries either through the implementation of specific countermeasures or through the natural evolution of vehicle styling changes. Evaluating pedestrian impact studies performed 10 years apart, Takeuchi et al. (1998) identified a 90% decrease in AIS 3+ pelvic fractures that was partially attributed to a transition in the vehicle body shape from a V-shape (i.e., bonnet leading edge angle less than 60° or a BLE lower than 70 cm) to a pontoon-shape (i.e., the bonnet leading edge is equal to or greater than 60° and a bonnet edge equal to or greater than 70 cm). In a similar study, Foret-Bruno and Faverjon (1998) demonstrated a pedestrian age dependence on changes in fracture patterns with vehicle design. For adults aged 12 to 49 years, however, they found a decrease from a 21% fracture rate in impacts with older vehicles to a rate of 0% in impacts with newer vehicles. For adults aged 49 years and older, the pelvic rates were comparable between both vehicle groups.

The pelvis seems to be most susceptible to damage by direct contact with the BLE, causing fracture of the iliac crest or the hip joint socket. Snedeker et al. (2003) confirmed that BLE was most critical in vehicles that presented a leading edge height between 750 and 850 mm, and the hood roundness was shown to make a difference between a predicted fracture condition and no-fracture condition. The BLE is responsible for approximately 42% of pelvic injuries for passenger car impacts and 27% of pelvic injuries for sport utility vehicle (SUV) impacts (Okamoto et al. 2001). Longhitano et al. (2005) showed vehicle-specific incidences of pelvic injury with noted increases in frequency and risk for SUVs, light trucks, and vans. More recently, Kerrigan et al. (2012) performed an analysis of 17 postmortem human surrogates (PMHS) impact experiments colliding with 5 different vehicle geometries, showing that the most extensive pelvic injuries occurred in the tests involving SUVs. Okamoto et al. (2001) showed that hip contact forces generally increase with increasing front end height. Ashton (1981) also showed a definite correlation between occupant height and bonnet height in determining the likelihood of pedestrian pelvic injury. Given the generally shorter stature of females, this may partially explain the relatively greater risk of females for pelvic injuries. Nevertheless, the vehicle is not responsible for all pelvic injuries. Otte and Huefner (2007) observed that one third of injuries to the pelvis (31%) were caused by impacts with the front edge of the hood and another third (32.9%) by a secondary impact on the road surface.

Pelvic injuries can occur independently or in conjunction with femoral injury. In addition to direct contact with the pelvis, contact with the BLE causes bending of the femur and reaction forces in the joints at the end of the femur, particularly at the hip joint. Injuries of the acetabulum generally result from concentrated loading at or below the head of the femur following contact of the femur at the greater trochanter. It is possible that with distributed forces at the hip level some of the forces are transmitted to the pelvic girdle through the soft tissue, thus limiting the forces applied through the hip joint itself. However, when there is a concentrated load on the greater trochanter, there is not the same force transmission through the soft tissue. As a result, the forces applied through the hip joint are not limited in the same way and an acetabular fracture is more likely to occur. If this is indeed the mechanism, then the addition of more compliant front structures will likely result in pubic rami fractures rather than acetabular fractures, when the forces exceed the pelvic tolerance level. When evaluating potential trade-offs between injury locations, however, it is important to consider that, clinically, the loss of integrity at the rami or pubic symphysis is managed more easily than injury at the acetabulum (Plummer et al. 1996).

Experimental Investigations Impacting the Pelvis Laterally

Numerous studies have been performed to study lateral loading of the pelvis for pedestrian and side impact conditions, mostly in a seated position. A fairly comprehensive review of these studies was provided by Plummer et al. (1996). In this parametric finite element (FE) study, the authors identified and selected a substantial number of representative studies and provided commentary on the methodology, results, and conclusions.

Fayon et al. (1997) performed free-fall experiments involving 18 PMHS applying different offsets (i.e., standoffs) between the thorax and pelvis that affected the sequence and distribution of loading. The drop height ranged between 0.5 and 3 m. The most frequent injuries found were to the ischio and illio pubic branches. The subjects displayed no injuries for pelvic accelerations up to 50 *g* over 3 ms.

Additionally, Tarriere et al. (1979) performed free-fall experiments involving 26 PMHS, where the drop heights ranged between 0.5 and 2 m and padded surfaces covered the rigid striking surfaces. The most frequent injuries were of the ischio and ilio pubic branches. An acceleration range between 80 and 90 *g* during 3 ms was considered a conservative level of human tolerance.

Cesari and Ramet (1982) and Cesari et al. (1980) conducted 31 PMHS impact tests with a 17.3 kg impactor measuring 175 mm in diameter with a rigid spherical radius of curvature of 600 mm, and the speed range was between 5.83 and 14.44 m/s. The study involved more than 90 different tests and showed a good correlation between the experiments and actual pedestrian crashes for minor pelvic injuries. However, pelvic rami fractures were nearly always limited to the struck side and the bilateral fracture patterns observed in actual crashes were not reproduced. This difference was attributed to applying energy only to the onset of fracture rather than reproducing the energy levels involved in actual crashes. The admissible impact tolerance was established as 4 kN for 5th percentile females and 10 kN for 50th percentile males.

In subsequent static tests with 5 isolated hemipelves, Cesari and Ramet (1982) found that a lateral load applied through the femoral head produced the highest strains in the proximity of the rami, which supports clinical findings that suggest that this region is the most likely to fracture. In similar tests, Scales (1993) identified 6 isolated pelves where the highest strains occurred in the rami but recorded the greatest strains in the inferior rami. This conflicts with the study by Cesari and Ramet (1982), which suggested an initial fracture of the superior rami. Although these strain differences may result from minor deviations in boundary condition and rates of loading, both studies demonstrate the susceptibility of the rami for fracture initiation in lateral loading.

Nusholtz et al. (1982) tested 12 PMHS using a flat pendulum impactor with a mass of 25 or 56 kg and a speed between 5.11 and 8.61 m/s. Only in 6 cases were pelvic fractures reported, and no good correlation was determined between the presence of injury and recorded acceleration or force levels.

Nusholtz and Kaiker (1986) tested 20 PMHS using 3 different impactors: a cannon, a ballistic pendulum, and a linear pendulum. They identified the shape of the hip joint as a fundamental source of variability in PMHS pelvic impact tests. During impact, the rotation of the femoral head in the acetabulum was an unpredictable function of the geometries, the degree of entrapment of the proximal femur by the padded impactor, and the population variations in soft tissue thickness and distribution. This variability precluded the determination of a single pelvic tolerance criterion such as maximum force or peak acceleration response. However, they did conclude that energy-absorbing and load-distributing materials are effective methods of transmitting greater amounts of energy to the pelvis without damage being produced and showed that, with the addition of padding, the fracture location shifted from near the acetabulum to near the pubic area.

Viano et al. (1989) tested 12 PMHS in side impact sled tests at a speed of 6.7–10.5 m/s, using a flat rigid impact surface with pelvic offset, and determined that 27% compression of the pelvic width correlates with a 25% probability of serious pelvic injury. The researchers concluded that pelvic compression correlated to pelvic injury more closely than either force or acceleration.

Similarly, Cavanaugh et al. (1990) tested 17 PMHS at speeds between 6.7 and 9.0 m/s. They recommended using the product of maximum normalized compression and maximum velocity to predict pelvic fractures and provided an injury threshold, $V_{\max} C_{\max}$, of 2.7 m/s at 25% probability of fracture. Cavanaugh et al. (1990) also established the limit peak force at 8 kN for the same probability of fracture and the compression of 16.3% measuring the pelvic width.

Additionally, Zhu et al. (1993) considered a lateral test series involving 17 PMHS against a flat wall at speeds ranging between 6.7 and 9.0 m/s with various levels of padding and pelvic offset distances. The researchers determined that the impact force was found to be a good predictor of pelvic injury. The researchers established a force injury criterion of 5.0 kN for 25% probability of AIS 2+.

Molz et al. (1997) tested 21 pelves using a drop tower device. The pelves were impacted with masses ranging from 14.2 to 25.2 kg and velocities from 4.1 to 6.4 m/s. The combination of neither fracture nor a displaced acetabular fracture in the test suggested that a 4.5 m/s impact with a 25.2 kg impact mass was just below the fracture tolerance of human pelvis.

Guillemot et al. (1998) tested 12 pelves using a controlled falling mass of 3.68 kg at a speed of 4 m/s. The impact was delivered on the acetabulum through a metallic sphere. Only 2 pelves were intact after the impact, and the 10 others exhibited a great variety of fractures, from a single public ramus fracture to the complete pelvis crush. The energy threshold for the pelvis fracture was determined to be 30 J. This low energy, compared to other studies, could be explained by the energy transference that the sphere could transmit to the pelvis structure.

Arbelaez et al. (1998) conducted drop test experiments involving 15 pelves impacted at 2 loading rates, 8.16 and 1.59 kN/ms. The masses ranged from 13 to 45 kg, and velocities ranged from 1.88 to 4.57 m/s. The higher applied loading rate resulted in acetabular fracture in 4 of the 9 cases. The lower loading rate applied resulted in rami fracture in 5 of the 6 cases, suggesting that the type of pelvic fracture was rate sensitive. The rate sensitivity of pelvic fractures identified by Plummer et al. (1996) suggests that force alone is not sufficient as a predictive variable. Variability of the area of pelvic contact, as well as the sensitivity of the measured force to elastic, viscous, and inertial contributions, indicates that compression (i.e., ultimate strain in the cortical or trabecular structures), or a composite of compression with other engineering variables, may be better predictors for bony fractures.

Bouquet et al. (1998) performed 11 tests involving 11 PMHS with a guided horizontal impactor. The masses were either 12 or 16 kg, and the speed ranged from 9.47 to 13.7 m/s. The impact surface was 200 × 200 mm. These tests were added to 20 previous experiments to increase the statistical power, and the injury probability curve was calculated using logistic regressions. Different criterion values for human pelves with a 50 percent probability of AIS 2+ were obtained: deflection of 46 mm, viscous criterion of 0.62 m/s, and an applied force of 7.6 kN.

Matsui et al. (2003) conducted 12 impact tests with a standing position for the PMHS pelvis. It appears that the impactor struck the head of the femur and part of the greater trochanter. The pelvis was restrained on the contralateral side by either a bolt attachment (12 PMHS) or a distributed block (2 tests). Tests with the bolt resulted in anterior pelvic ring fractures, whereas the block tests resulted in pubic rami fractures of lesser severity. The authors noted that little deformation of the pelvis was required to fracture the rami, and they hypothesized that most of the deformation in the bolt tests was produced following fracture (although they detected the time of fracture from a drop in force, they did not correlate this with the corresponding displacement at the same time). The authors recommend force as an injury criterion for pelvic fracture. For pelvic fracture, 50% risk was defined at 9.6 kN.

Beason et al. (2003) impacted 12 cadaveric pelves at the greater trochanter using a custom-designed drop mass device. The soft tissues and muscles were removed from the pelves, and 6 pelves were impacted without padding and 6 were impacted with padding. Five of the 6 unpadded impacts resulted in pelvic fractures, and 4 of the 6 padded impacts resulted in fracture. In all cases, the rami was fractured and the average peak loads were 3490 ± 1380 N. The maximum compression tolerance at 25% probability of pelvic fracture was 6.92% and the $VC_{\max}$ was 0.09 m/s. Mean $F_{\max}$, $C_{\max}$ and calculated tolerances for $VC_{\max}$ were lower than those established in previous studies due to the removal of soft tissues from the pelves prior to impact. Bone mineral density BMD was found to be significantly correlated with peak fracture force and maximum ring compression of the fractured pelves.

Snedeker et al. (2005) performed 5 full-scale vehicle–pedestrian impact tests, involving a simplified buck representation of a simulated car shape traveling at 40 km/h. Each PMHS was instrumented with 10 strain gauges affixed to the pelvis and femur to measure cortical bone surface strains for validation of a human FE model. There were a variety of pelvic injuries in the 3 subjects, mostly involving the public rami, illium, and acetabulum. The 10 kN peak impactor force threshold proposed by Cesari and Ramet (1982) yielded a good correlation with the human FE model injury prediction, as validated by the strain gauges measurements.

Leport et al. (2007) conducted 16 impact tests on 8 PMHS in a seated position for the PMHS pelvis, measuring the Fy and Mz at the pubic symphysis location. Two different impactors were used, one for each side of the pelvis. The right side of the PMHS pelves was impacted by a rounded impactor described by Cesari et al. (1980) and the left side was impacted with a Heidelberg pelvic plate. The ratio between the peak external

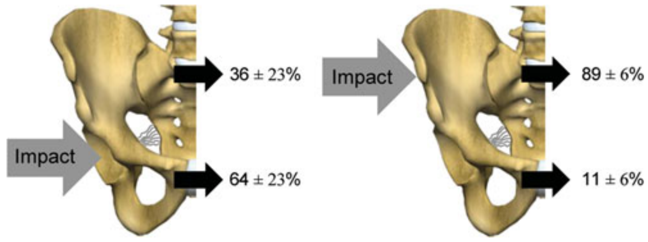

Fig. 4. Load distribution at peak force for dynamic tests, based on Salzar et al. (2009).

force and the peak pubic force was calculated for each subject and a mean ratio was calculated. By combining these results with existing literature, data injury risk curves, as a function of the pubic force, were developed. A probability above 40% of pelvic fracture was determined for a pubic force measured in the PMHS of 3 kN.

Salzar et al. (2009) conducted drop tower test experiments involving 12 human pelves dynamically to determine the internal load distribution through the pelvis bone depending on the loading location. The impactor mass was 76.6 kg and velocities ranged from 1.72 to 3.02 m/s. Their research determined that for impacts applied to the acetabulum, forces were distributed between the pubic symphysis and the sacrum. For the dynamic impacts applied directly to the acetabulum, the pubic symphysis loads were 64% of the total load transmitted, whereas for the ilium impacts, the pubic symphysis loads were 11% of the total load transmitted (Figure 4).

From ilium impact, the load at fracture was 420 ± 390 N in the pubic symphysis and 3110 ± 1470 N in the sacrum. Loading the acetabulum, the load at fracture was 1910 ± 930 N in the pubic symphysis and 1020 ± 630 N in the sacrum.

Tables A1 and A2 (see online supplement) show a summary of the studies conducted to determine an applicable injury criterion for the pelvis.

Though pelvic injuries sustained in pedestrian–vehicle crashes and side impacts ostensibly share some common attributes, there are differences that exist that may caution against combining the occupant and pedestrian data sets. Ikeda et al. (2012) and Takahashi et al. (2011) have shown the differences in pelvic loading during pedestrian impacts due to vehicle type using a human body model. These may include differences in contact properties (exterior of vehicle front vs. door interior/intrusion), differences in loading vector (Takahashi et al. 2011), weight bearing (pedestrian vs. occupant), and femur orientation relative to the pelvis. In general, the change in velocity characterized by vehicle contact with the pelvis for a pedestrian (cf. Kerrigan and Crandall 2007) and an occupant in a side impact (cf. Kent and Crandall 2000) show considerable differences when the pelvis contacts the door in a side impact (Side Impact New Car Assessment Program [SINCAP] in the example) vs. a vehicle (mid-size sedan at 40 km/h).

European Enhanced Vehicle-Safety Committee Pedestrian Upper Legform Impact to Bonnet Leading Edge Procedure

The European Enhanced Vehicle-Safety Committee (EEVC) developed test specifications and rating systems for assessing the pedestrian injury potential of vehicle front structures. A voluntary agreement proposed by European automotive manufacturers stipulated that all new cars types introduced after October 1, 2005, should comply with EEVC pedestrian safety test requirements (Directives 2003/102/EC and 2005/66/EC), posteriorly repealed and updated by Regulation 78/2009.

For protection of the pelvic and thigh region, an upper legform impactor was utilized, only for monitoring purposes, to evaluate the vehicle front. The design philosophy of the impactor and test method was to reduce the interactions between the proximal lower limb and the bonnet leading edge while taking measurements that can be used to reduce the risk of femur and pelvic fractures (Lawrence and Hardy 1998).

The impactor consisted of a guided simulated femur structure covered by compliant viscoelastic foam. Two load transducers were mounted at either end of the impactor and bending moments were measured via strain gages mounted on the simulated femur (in 3 locations, upper, middle, and lower legform). The impactor velocity and impact angle were based on the shape of the vehicle (i.e., bonnet leading edge and bumper lead). Energy levels were supposedly adjusted to account for the rotational and translational (e.g., sliding) motion that occurred in actual pedestrian–vehicle impacts. The test was performed at an impact speed up to 40 km/h. The instantaneous sum of the impact forces with respect to time should not exceed a possible target of 5.0 kN and the bending moment on the test impactor is recorded and compared with the possible target of 300 Nm.

Although the injury mechanisms of the pelvis (i.e., a fairly concentrated mass) and the femur (i.e., a long shaft) are different, the EEVC procedure used the same test device and the same injury criteria (Lawrence and Hardy 1998). Okamoto et al. (2001) showed that for SUVs, the risk of pelvic fracture is dependent only on the contact force generated from the pelvis impacting the bonnet leading edge and is not transmitted through bonnet leading edge contact with the femur. From epidemiologic data, Edwards and Green (1999) indicated that the femur and pelvis have the same injury contact source in only 5% of the pedestrian–vehicle cases. Snedeker et al. (2003) showed that there was no correlation between the EEVC test results (simulated) and observed injury using a computational model (THUMS) due to the variance associated with where the force was directed.

Meanwhile, Ehrlich et al. (2009) studied autopsy protocols in Berlin, including parts of the records of the judicial inquiries from 2 different periods involving fatal pedestrian vehicle collisions: group A, 1978–1985, and group B, 1991–2004. The main findings showed that between periods A and B, head injury decreased from 35% to 27%, but polytrauma cases increased from 15% to 37%. Comparing the injury types, a distinct improvement could be found in accidents with small-class cars: though relevant injuries of head, neck, chest, and the legs decreased in period B, pelvic fractures occurred more frequently. Pedestrians injured by medium-class and high-class cars in period B sustained skull fractures, significant intracranial hemorrhages, and cervical and femoral fractures less frequently than in period A butexperienced rib and pelvic fractures as well as intra-abdominal injuries more frequently.

An evaluation of the effectiveness of pelvic injury countermeasures designed using the EEVC procedures will have to wait either for updated epidemiologic data from pedestrian crashes with vehicles designed with EEVC testing considerations or for comparison studies between the EEVC test results and corresponding PMHS impact tests.

Despite the sturdy construction of the pelvis, pelvic fractures are a common consequence of pedestrian–vehicle impacts, mostly in cases of collision with SUVs, light trucks, or vans. Because those vehicles are growing in popularity in Europe and the United States, pelvic injuries appear to be increasing with the corresponding changes in the vehicle fleet.

The severity of damage to local vascular and nerve structures and the associated injuries to other body regions result in a relatively high mortality rate for pelvic fractures. The diminished bone density and shorter stature of elderly females make them particularly susceptible to pedestrian pelvic injuries. Fractures of the rami are the most common injury site and are predicted by experimental models of pedestrian loading conditions..

Some of the experimental testing cited in the article was focused on lateral impacts to the pelvic region but was not specifically focused on the rates of loading and configurations (i.e., standing human) that are specific to pedestrian–vehicle impacts. Though a reduction of forces and moments in this region will certainly be beneficial to a pedestrian in an accident condition, it is unclear as to the extent of correlation between many of the test conditions and real-world loading patterns. Though compression of the pelvis is likely a reasonable indicator of overall pelvis fracture risk, a number of factors such as combining the force, acceleration, velocity, and compression have been assessed as potential predictive variables by researchers. In particular, the use of force as the predictor of tolerance has a very large inconsistency, likely due to sensitivity of the force to loading rate and contact area.

Though there have been changes in the vehicle fleet over the years, pelvic fractures as a result of pedestrian–vehicle impacts are still prevalent. Therefore, continued updates of epidemiological information will be required to monitor and assess trends in pedestrian pelvis injuries as they related to vehicle designs. Recent advances in pedestrian crash avoidance technologies will complement existing passive countermeasures, mostly focused on increasing the front-end deformation and the energy absorption. In order to make further gains in the passive protection of pedestrians, additional biomechanical experiments will be required to determine a more definitive and specific injury risk function for pelvic structures.

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Supplemental Material

Supplemental data for this article can be accessed on the publisher's website.

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