INJURIES ANALYSIS AND COMPUTATIONAL SIMULATION OF TWO WHEELERS ACCIDENTS USING HUMAN BODY BIOMECHANICAL MODELS

Sérgio David Parreirinha Carvalho

sergio.carvalho@ist.utl.pt

INSTITUTO SUPERIOR TÉCNICO, UNIVERSIDADE TÉCNICA DE LISBOA, PORTUGAL

Abstract

Road accidents investigation is a worldwide major concern, playing an important role in reducing the number of victims by implementation of measures to avoid or minimize the accidents occurrence, or reduce the injuries severity of the victims. This work's objective is to validate criteria for injury severity score evaluation in two wheelers (TW) road accidents victims. The validation of the criteria is achieved by comparison of the obtained results from accidents reconstitution with clinical and/or medico-legal autopsy reports from INMLCF (National Institute of Forensic Medicine) data base.

The methodology establishes injury criteria for each body segment. Body segments considered are head, neck, thorax, abdomen, pelvis, lower and upper extremities. Twenty case studies are used and in each one a simulation is validated using multibody. The injuries for each body segment are obtained in an AIS (Abbreviated Injury Score) evaluation, except for the upper extremities, where only fractures occurrence are used, based on risk factor. Using the data available from clinical and/or medico-legal autopsy reports, the results from simulations are compared as global, *i.e,* the mortality probability, using the ISS (Injury Severity Score) globally, and locally using the AIS.

The applied methods enable to evaluate globally the life risk of the TW accidents victims, and locally the lesions severity in each body segment considered. Moreover, an example is included to demonstrate that this method is suitable to be used in the reverse approach, *i.e,* use the victim's injuries severity data to optimize the accident reconstitution simulation.

Keywords: Two Wheelers, Accident Reconstruction, Injury Severity, Impact Biomechanics, Multibody.

1 Introduction

Road accidents have been focused from several decades with a more a more importance. Even though many investments have been made, the statistical indicators don't lie, and in spite of many measures already implemented, many more will have to be accomplished in order to further reduce the road accidents and, consequently, the health burden translated in injury, disability and deaths.

Governments and vehicle manufacturers spend billions of dollars annually in order to try to reduce the avassalating figures. All these investments on engineering evolutions of the vehicles safety systems, road construction, regulation, education, improvement in the quality of political institutions, medical care and technology developments, have contributed to reduced motorcycle deaths [Law *et al* (2009)].

Although every road accident is potential to cause physical damages in all individuals involved, more critical effects on life threatening, are accidents involving the occupants of two wheelers – TW - (bicycles and two wheelers motorcycles and mopes – PTW – Power Two Wheelers). Motorcycle occupants are above than 30 times more likely to die in a traffic crash than a car occupant [Lin and Krauss (2008)]. This occurs primarily due to the absence of a rigid structure involving the occupants, which in case of a collision, acts as a protection shell. With the energy dissipation on this shell, the values received by the occupants for the same conditions, are always higher when comparing with any other terrestrial vehicle. Besides the capsule protection, safety increasing rules demand cars and trucks to be equipped with further additional safety systems, the so called passive safety systems. These systems acts in order to minimize occupant's injuries, in case of a crash occurrence, *e.g,* airbag systems, seat belts, emergency braking system. TW offer almost no additional safety beyond the helmet protection and protective clothes, especially in bicycles, where the mandatory use of helmet protection is still optional in Portugal, leaving to the free choice of the occupants. Today this safety equipment is available in high quality materials and there are helmets and jackets equipped with airbag systems. Using of special motorcycle riders protection clothes (jackets, pants and boots) may also play a role in reducing accident injuries [Rome (2006)]. Taking into account the evolution on the equipment available for TW occupants such as, the design of the helmet, which may increase protection on Direct Force Effects (DFE) [Richter *et al* (2001)] and thus reducing head and brain injuries in case of accident [DeMarco *et al* (2010) and Dee (2009)], the combination of these protections assumes a practical mean, especially if the crash occurs at a reasonable low speed, which covers a significant amount of crashes involving two wheelers [Bernardo (2012)].

Considering all the measures implemented to prevent accidents occurrences, or minimizing their consequences, the yearly number of deaths and serious injuries has been decreasing in the past few years in Portugal. However, the values still remain within the higher values if considering EU indicators [Dias and Paulino (2007)].

The use of TW is more and more popular, especially in the cities. The major advantages are the cost efficiency (gas millage and maintenance savings), parking facilities, time savings, and lower acquisition cost, when compared to a car. Additionally, small distances within urban areas became even more cost efficient if using a bike. Fuel savings allied with physical exercise and considering the construction of lanes for bike users, are additional incentives for the use of this mode of transport.

The major disadvantage for all TW is the potential and constant life threatening of the occupants in case of accident due to the reasons already mentioned.

About the use of other safety equipment, ANSR (National Road Safety Authority) database only includes for TW if the occupants were using or not the helmet. Table 1.1 summarizes the values of fatalities rate per 100 accidents occurrence in Portugal (2011), comparing the victims who wore helmet and those who didn't.

Table 1.1 - Fatality rate per 100 accidents for victims wearing or not protection helmet in Portugal (2011).

TW	Victims with helmet	Victims without helmet
Motorcycle	2,4	16,4
Moped	1,3	3,1
Bicycle	1,3	3,1
Total	2,2	3,7

Observing table 1.1, the fatality rate increases when victims are not wearing helmet protection. For motorcycles the risk factor increases 5 times. Globally, *i.e*, considering the TW group, the risk increases about 70%, which states for that the use of safety helmet, may have a significant role in reducing the injuries in case of accident, as already pointed in Bernardo (2012) after a detailed statistical analysis.

"Vulnerable road users" stands for users with no primary protection systems in case of accident, *i.e*, without the shell protection of a vehicle, like TW vehicle occupants and pedestrians. Using all the information about accidents involving TW and the involving victim's injuries, enables to predict which parts of the body are mainly affected for each collision scenario and other variables involved in the accident, such as the protection equipment, impact speed, and type of vehicle, among others. This approach enables to assess the risk factors for TW users and isolate the critical items, in order to implement procedures in vehicles, traffic rules, laws, actions to increase the level of awareness of road users, *etc*. The main goal is traffic safety increase in order to reduce the number and injuries severity of road accidents.

The present work is included within injury and impact biomechanics, belonging to the road accidents investigation group from mechanical engineering department of IST (Faculty of Engineering of Lisbon) in cooperation with INMLCF (National Institute of Forensic Medicine) and the Portuguese national project "safety of vulnerable road users".

Knowledge of injury mechanism that result from accidents of TW is very important considering the project of the vehicles in order to prevent the accidents, reduce the severity of injuries and to complement the overall investigation. Accident investigation is a very complex task, not only due to the lack of accurate data (rest positions of the vehicles, occupants, debris, fluids, witnesses, personal reports, *etc*.), but also the dynamics reconstitution complexity, caused by the innumerous amount of variables presented in these situations and the reduced time interval of the occurrence [ACEM (2003)]. The inclusion of the injuries in mathematical and computational models for the analysis, represents enhanced valued for a correct and more detailed reconstitution of the accident conditions. One of the most crucial variables is the definition of a reasonably correct point of impact. The correlation of the lesions of bicycles and PTW occupants and foot passengers with the accident dynamics, is very important to achieve a more accurate location of impact. Thus the prevention and mitigation of the consequences of these accidents, and also the input responsibility of the involved parts can only be determined if the injuries are correlated with the accident dynamics.

The objective of this work is to establish correlation models between the injuries resulting from an accident and the conditions that gave origin to it. A detailed analysis of the body damages is performed recurring to medical clinical data from the victim's assistance and/or the medical-legal autopsy reports. With the data included in the accident reports (from the insurance company or police authorities), a reconstitution of the accident is accomplished recurring to a commercial computational software application, the PC-Crash^{TM} with multibody [Moser *et al* (1999) and Clief *et al* (1996)]. Using multibody dynamics analysis (in special accelerations, speeds and forces) and recurring to injuries biomechanics criteria in the literature, it is established a correlation between the results from the mathematical models for the injuries and the real medical observations included in reports (in clinical or forensic settings). When a reasonable correspondence is achieved, it's possible to validate the reconstitution and the conditions that motivate the occurrence, in special speeds and vehicles maneuvers. This provides ways to determine the occurrence of a certain kind of injuries with the type of collision, and plays a very important role on the measures to avoid or mitigate them.

2 Methods

In order to accomplish the objectives, this chapter describes the sequence of procedures adopted throughout this work for the accidents data analysis. It is indicated and justified the criteria for selection of the case studies as well as the methods for injuries analysis and severity evaluation, based on the information available from the PC-Crash^{TM} simulations. It is included also an overview of the risk factor concept, an useful criteria when the comparison with a single upper limit value from the literature is the only tool available for injury prediction in a certain body segment.

2.1 Injury Criteria

Several models exist for injuries prediction in human body when this is subjected to forces, accelerations, moments or energies sufficient to cause organs and tissues damages. In case of road accidents, the main cause for lesions is impact due to the need of mechanical (kinetic) energy dissipation. In this section a few methods for injuries evaluation are presented. These were chosen in an attempt to best fit the situation of accidents involving TW occupants, the type of impact, and the variables that can be calculated recurring to PC-Crash^{TM}. There are situations of lesions in the same part of the body that may be determined using different models since it depends on if it is a front or a rear-end impact. Other situations may use a criterion that, according with the literature, may not be the best to fulfill the scenario, but, due to limitations on the software, it reveals to be the suitable way to get information for analysis. These situations are explained in the next sub-sections.

The lesions estimation using the models, are within a methodology of comparing values with a scale, in order to predict the severity of the injuries. The scale used is the AIS. Tables are available in the literature to correlate the lesions described in medical reports and this AIS scale for the different body segments [Schmitt *et al*, 2007]. The main objective is to establish a correspondence between the AIS predicted by the model, and the AIS obtained recurring to clinical and/or medico-legal autopsy reports data, enabling to validate the model for injuries prediction. This is done separating the lesions in body segments and thus applying the criteria according with the accident reconstitution. The body segments include: head, neck, thorax, abdomen, pelvis, lower and upper extremities, *i.e*, lower and upper limbs. This division is inspired within the current practices described in literature.

2.1.1 Head Injuries

The most important lesions on the head are those involving either the skull or the brain, including the meninges. Injuries on the head may be caused by situations where direct contact of the head has occurred (contact forces), or no direct contact has occurred, and in this case, the only lesions responsible mechanisms are the inertial forces, *i.e*, accelerations (or decelerations). Several studies were performed in cadaver using drop tests to determine the limit impact force to cause skull fractures. A compilation of those studies may be found in Schmitt *et al* (2007) and is summarized in table 2.1.

Table 2.1 - Peak force for fracture at different regions of the skull [Adapted from Schmitt et al (2007)].

Impact Area	Criterion	Force (kN)
Frontal	# 1	4.2
	# 2	5.5
	# 3	4.0
	# 4	6.2
	# 5	4.7
Lateral	# 1	3.6
	# 2	2.0
	# 3	5.2
Occipital	# 1	12.5

For lesions caused by accelerations, experimental studies were addressed to measure limiting values for diffuse brain injuries and subdural hematoma. Ommaya *et al* (1967) measured angular accelerations in primates, assessed the injuries level and extrapolate limiting values for human brain with a probability above 90% to produce concussions. It was found that the injuries caused by angular acceleration depend on the mass of the brain. On this basis, the extrapolation of Ommaya *et al* (1967) results for humans considers this mass scale between the primates and human brain. Schmitt *et al* (2007) compiles several studies on the limits of angular velocity and acceleration and the respective brain injuries obtained (table 2.2).

Table 2.2 - Tolerance thresholds for rotational acceleration and velocity of the brain [Adapted from Schmitt et al (2007)].

Tolerance Threshold	Type of Brain Injury
50% Probability: **α = 1800 rad/s2 for t < 20 ms** **α = 30 rad/s2 for t > 20 ms**	Cerebral Concussion
α < 4500 rad/s2 and/or ω < 70 rad/s	Rupture of bridging vein
2000 < α < 3000 (rad/s2)	Brain surface shearing
ω < 30 rad/s **safe: α < 4500 rad/s2** **AIS 5: α > 4500 rad/s2** **ω > 30 rad/s** **AIS 2: α = 1700 rad/s2** **AIS 3: α = 3000 rad/s2** **AIS 4: α = 3900 rad/s2** **AIS 5: α = 4500 rad/s2**	General Injuries

Since PC-Crash^{TM} calculates contact forces, angular velocities and accelerations, comparisons may be made between the obtained values and the limiting values from previous tables.

Another method for head injuries estimation is the HIC. This is a largely accepted criterion based on head acceleration values. HIC is computed based on equation 1.

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} \right\}_{max} \tag{1}$$

Where *a(t)* is the acceleration resultant in gravitational acceleration units [g] obtained in the head centre of mass. t_2-t_1 interval is chosen up to a maximum of 36 ms (FMVSS 208). Minimum HIC threshold for injuries to occur is 700 for 15 ms and 1000 for 36 ms. Beyond these values, severe and permanent head injuries are expected.

PC-Crash^{TM} doesn't permit to include helmet accessory within the multibody system. An alternative, also used by Bernardo (2012) is based on the work of Liu *et al* (2008), who predicted a reduction in head lesions severity when using the helmet. The correction factors applied by Liu *et al* (2008) depend on the determined injury scale, according with equations 2 and 3.

$$HIC_{Helmet} = 0.31\, HIC_{No\ Helmet} \qquad for\ AIS < 6 \tag{2}$$

$$HIC_{Helmet} = 0.58\, HIC_{No\ Helmet} \qquad for\ AIS = 6 \tag{3}$$

Establishing correlations of HIC with injury scales, Kuppa (2004) provides some data upon Head Injury Risk Curves. Considering normal distribution, the probability of head injury as a function of HIC is given by equation 4.

$$p(Head\ Injury) = \varphi \left[\frac{\ln(HIC_{36}) - \mu}{\sigma} \right] \tag{4}$$

Where φ is the cumulative normal distribution, μ=6.96352 and σ=0.84664 values for AIS ≥2 head injuries, μ=7.45231, σ=0.73998 for AIS ≥3 head injuries, and μ=7.65605, σ=0.60580 for AIS 4+, *i.e*, 4<AIS<5 head injuries.

A more fine correlation between AIS and HIC may be found in Hayes *et al* (2007). This correlation (figure 2.1) determines the probability of AIS 1 to 6 as a function of HIC.

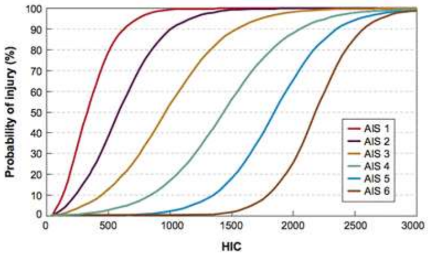


Figure 2.1 – Head injury risk curves based on HIC values [Hayes et al (2007)].

By observing the diagram from figure 2.1, it can be concluded that from HIC values above 2000 a serious life threatening risk exists, *i.e*, AIS 5 or above.

2.1.2 Neck Injuries

In automotive crashes, loading of the neck is generally due to head contact forces and/or combined axial or shear load with bending.

Schmitt *et al* (2007) presents several criteria for spine injuries evaluation. Using PC-Crash^{TM} multibody systems, all the parts of the occupants correspond to rigid bodies and consequently, below the neck, all vertebrae are included within the thorax. The only vertebrae that might be considered separately are within the cervical segment of the spine. Based on Viano *et al* (2001) upper cervical injuries include the critical spine lesions that may represent a life threatening.

NIC (Neck Injury Criterion) is a very useful method applicable for accidents which the impact is mainly to cause reaction in anterior-posterior direction, *i.e*, x-axis. The main limitation in applying this criterion is the inability in attributes AIS score to the obtained results.

Other criterion for neck injuries is the N_{ij} for frontal impacts. This criterion combines axial force (z-axis) with flexion or extension bending moment in sagittal plane (y-axis), to provide a composite neck lesions indicator, according with equation 5.

$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \tag{5}$$

F_{int} and M_{int} are normalizing factors, called intercept values. For an adult test dummy, FMVSS 208 defines the intercept values according with table 2.3:

Table 2.3 – Normalizing factors for Nij calculation.

Fint		Mint	
Compression	Tension	Flexion	Extension
6160 N	6806 N	310 Nm	135 Nm

An injury threshold value of 1.0 applies for each load case, leading to AIS ≥ 1. A diagram correlating N_{ij} with AIS above 3 occurrence probability may be found in Eppinger *et al* (1999). These results are corroborated by Hayes *et al* (2007) who extended this correlation between N_{ij} criterion and the probability of AIS occurrence from 2 to 5. These results are represented in figure 2.2.

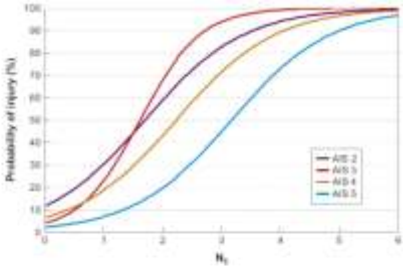


Figure 2.2 - AIS 2, 3, 4 and 5 probabilities as a function of Nij [Adapted from Hayes et al (2007)].

Although PC-Crash^{TM} doesn´t provide calculation of momentum, it does for angular velocity and thus,

$$M_y = I_{yy} . \alpha_y \tag{6}$$

Equation 6 may be found *e.g* in Beer and Johnston (2009), being I_{yy} and α_y the MOI (Moment Of Inertia) and angular acceleration in y-axis respectively. Yoganandan *et al* (2009) performed a detailed study, correlating mass, gender, height and weight with MOI. For calculation simplification it is used, throughout this work, inertial properties of the head corresponding to 50th of male percentile resumed in table 2.4.

Table 2.4 – Mass and MOI for head corresponding to 50th male percentile.

Head Inertial Properties for 50th Percentile Male	
Mass	4.54 kg
I_{xx}	22.0 x 10-3 kgm2
I_{yy}	24.2 x 10-3 kgm2
I_{zz}	15.9 x 10-3 kgm2

These results may be found in Beier *et al* (1980), also validated by Yoganandan *et al* (2009).

2.1.3 Thoracic Injuries

Thoracic and abdominal lesions are directly correlated with the rate of deformation caused by the impact that occurs in both regions during the accident. The deformation, and consequently the lesions, depends on the kinetic energy, stiffness and the shape of the impact object, as well as the direction and point of contact. Usually impact lesions are blunt type. The lesion appears by smashing of soft tissue of the organs when the deformation is above the limits that still allows elastic recover. Skeletal lesions appear as bone fractures that may affect ribs, sternum, or vertebral column. In general, cases of thoracic lesions, these occur more often in internal organs such as esophagus, lungs, aorta, heart and diaphragm [Schmitt *et al* (2007)].

The inertia of internal organs may be associated with lesions that appear due to different moments between the organs and the thorax. This may lead to torn or rupture in the membrane that supports the organ, breakdown of arteries, especially in aorta.

Criteria for evaluation of thoracic injuries are very difficult to apply when using an accident reconstitution based on a multibody with rigid bodies. The most severe impacts with higher potential to cause thoracic injuries are the frontal and lateral. For lateral impacts, the TTI (Thorax Trauma Index) is most well-known acceleration based injury criterion. TTI requires lateral accelerations determined on 4th and 8th rib, and also 12th thoracic vertebra. Using PC-Crash™ there is no possibility of isolating accelerations on those three regions.

Other criterion is the rate of compression of the thorax, which in case of rigid models, lead to the same limitation. The compression criterion requires obtaining the deformation of the thorax, in accordance with equation 7.

$$C = \frac{d(t)}{D} \tag{7}$$

Where *d(t)* is the deformation of the thorax and *D* the thickness of the torso. King (2000) - Part 1 gathered several data concerning measure of chest stiffness in cadavers. Although some values were achieved, these can't be used for calculations because, according to Lobdell *et al* (1973), after using some volunteers for living experiments, concluded that depending on being tensed or relaxed, the stiffness gets different values. In case of tensed muscles, stiffness is increased when comparing with all the muscles relaxed, as it happens in a dead body. According with this study, the values reached for small values of compression are summarized in table 2.5.

Table 2.5 – Stiffness of thoracic muscles to compression force.

Thoracic Muscles	Tensed	Relaxed
Thorax stiffness to compression force	23.6 N/mm	7 N/mm

Melvin *et al* (1985) corroborated this value of 23.6 N/mm (± 4 N/mm) up to 40 mm of compression and stated an upper stiffness of 120 N/mm (± 18 N/mm) for compressions above 76 mm. This nonlinear relationship may be represented as:

$$F_x = -(0.48 \pm 0.07)d^2 \tag{8}$$

In equation 8, F_x is the compression force in the thorax, *i.e*, the force applied on the chest thought the anterior-posterior x-axis (N) and *d* is the amount of deformation (mm) suffered through the application of the force. This result was obtained for a static load, but in the same report, authors concluded that the maximum deflection of the chest occurs when the impact velocity and the chest reach a common velocity, and consequently the force at maximum deflection is primarily a static response making equation 8 still valid for this work purpose.

By obtaining the compression contact force recurring to PC-Crash™, using equation 8, the value of the chest deformation *d* may be obtained. Kroell *et al* (1971, 1974) correlated the maximum deformation (C_{max}) with AIS by analyzing blunt impacts, and concluded that his correlation was better than the tables using force and acceleration. This correlation corresponds to equation 9.

$$AIS = -3.78 + 19.56.C \tag{9}$$

Where *C* comes from equation 7, using *D* as 230 mm, corresponding to 50th male percentile. For lateral injuries quantification results are limited using these methods based on PC-Crash™ calculations. For this purpose, a comparison can be made, using those tables of limiting forces or accelerations. As discussed, although not being a good evaluation as the corresponding for frontal impacts, provides at least a way to fit the order of magnitude of life threatening in that body segment.

Kuppa (2004) estimated thoracic injury criteria using data from 42 side impact sled tests with cadavers. The purpose was to get values for maximum rib deflection. After statistical procedures, the level of injuries obtained within the tests was correlated with the spine lateral acceleration of the impact. Table 2.6 summarizes these data and correlates it with the probability of injury, considering AIS above 3 and 4.

Table 2.6- Predictor of injury severity in upper and lower spine caused by lateral accelerations [adapted from Kuppa (2004)].

Injury Predictor	**25% Prob. Of Injury**		**50% Prob. Of Injury**	
	AIS>3	AIS>4	AIS>3	AIS>4
Max Lower Spine Accel. **Std Error Range**	36g 0g - 59g	70g 2g - 114g	80g 54g - 112g	130g 96g - 170g
Max Upper Spine Accel. **Std Error Range**	15g 0g-30g	46g 25g-65g	43g 26g-60g	74g 58g-114g
Average Values	26g	58g	62g	102g

In spite of PC-Crash™ doesn't provide acceleration values for upper and lower spine, but instead just for torso region, this allows another comparison beyond the lateral loads. So, using the a_y values, it is possible to predict some additional injury scale, but, moreover, to have a qualitative order magnitude of damages in the spine. As stated previously, the same acceleration values produce more severe injuries if applied in upper spine, than in lower spine.

2.1.4 Abdominal Injuries

The direct abdominal impacts from the accidents are suitable to cause damages in the kidneys, liver and spleen. The organs in abdominal region are not rigidly fixed to the walls, but supported by membranes or embedded in fat, allowing them to move and adjust the body position and respiration or biomechanical inputs. This freedom of movement greatly influences the response of these organs to the injury mechanisms.

Many studies were made in animals and cadavers in an attempt to reach models for abdomen injuries quantification. King (2000) - Part 2 includes values for stiffness on lower abdomen bounded by the interval from 23.0 N/mm to 53.9 N/mm. This measurements result in highly nonlinear diagrams, because of the hysteresis effect, caused by all the complex mechanical behavior due to the anatomical characteristics.

Using the same software to obtain the kinetics of the accident, the same limitations previously applied to the thorax rise again. One possibility is consider that since abdomen is more exposed than the thorax, use as well for abdomen the thorax criterion, considering the contact forces on the torso. This is actually corroborated by Rouhana (1993), who recommended lower abdominal response to be used as for the thorax and upper abdomen.

Using PC-Crash™, a more refined approach may be used, since the values of contact forces are available for the hip. Seems quite reasonable to suppose that abdomen is exposed to force magnitudes somewhere between the values in both segments, *e.g*, the lower value of the upper limit in both areas, which may represent the threshold limit force reached in abdominal segment.

King (2000) - Part 2 compiled several results for abdominal tolerances for frontal and lateral impacts. Table 2.7 resumes the threshold limits of lateral and frontal forces, and the severity of injuries expected to occur in abdominal segment.

Table 2.7 - Abdominal tolerances for frontal and lateral impacts [adapted from King (2000) - Part 2].

Tolerance Level	Injury Level	Main Organ Affected
Front Impact		
0.24 kN	AIS>3	Liver
3.76 kN	25 % probability of AIS>4	Lower Abdomen
Side Impact		
6.73 kN	25 % probability of AIS>4	Upper and Mid Abdomen

Another injury criterion validated for this segment, is the viscous criterion [Viano *et al* (1989)]. In cases of severe impact, the injury level was correlated with the impact force. In this case, a statistic curve was obtained, considering the total (horizontal) force. The result is presented figure 2.3.

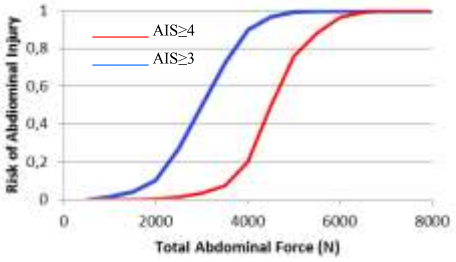


Figure 2.3 - Graphic representing the abdominal injury risk as a function of the horizontal abdominal force measured [adapted from Kuppa (2004)].

For the purpose of this work, a combination of King (2000) - Part 2 and Kuppa (2004) results is used for abdominal body segment.

2.1.5 Pelvic Injuries

Pelvic segment is often considered as pelvis and lower extremities, *i.e*, considering also the thigh, the knee, the lower leg and foot.

Since PC-Crash^{TM} enables to calculate the kinetics in the pelvis separated from the legs, it is worth try to obtain some separated criterion to quantify lesions in those segments separately. Injuries from accidents affecting pelvis and the lower extremities are usually fractures, so the main focuses of attention are the bones. According with Dalstra *et al* (1993), pelvic bones mechanical properties are not so far from isotropic, and the most severe injuries are consequence of side impacts [King (2000) - Part 2].

There are just a few works which attempt to measure hipbone mechanical properties. The most common is to get values of mechanical behavior for the joint between hip and femur [Dalstra *et al* (1993)], motivated for this quite frequent situation, especially in elderly people [Schmitt *et al* (2007)]. Many of the references on this matter use this type of approach. For frontal impacts, tolerance data for the pelvis are sparse. This is due in part to the lack of a single study involving a large number of cadaveric subjects. On the other hand, motivated by use of belt restraints in passenger cars, more lateral impact data is available, due to the higher occurrence of these injury type in car accidents.

King (2000) - Part 2 gathered an amount of data from several references in an attempt to achieve the tolerable load limits in pelvis. Tables 2.8 and 2.9 summarizes those values, the test type, *i.e*, the point of load application, and the expected injuries, for both frontal and lateral impacts.

Table 2.8 - Limit load criteria for injuries in pelvis motivated by frontal impact.

Criterion	Tolerance Level	Load Application	Injury Level
# 1	6.2 kN – 11.8 kN	Pelvis	Pelvic fractures
# 2	8.9 kN – 25.6 kN	Knee	Hip and/or pelvic fractures
# 3	37 kN	Knee	Hip and/or pelvic fractures
# 4	3.7 kN – 11.4 kN	Knee	Hip and/or pelvic fractures

Table 2.9 - Limit load criteria for injuries in pelvis motivated by lateral impact.

Criterion	Tolerance Level	Injury Level
# 1	4.9 kN – 11.9 kN (male) 4.4 kN – 8.2 kN (female)	Multiple fractures of the pubic rami
# 2	10.0 kN (male) 4.6 kN (female)	2<AIS<3
# 3	80 g – 90 g	Multiple fractures of the pubic rami

As it can be seen in table 2.8, many of the tests performed used the indirect fracture, *i.e*, with the load applied in the knee. This is perfectly reasonable when analyzing passenger car accidents, where the possibility of knees impact exists, transmitting the energy to the hip, while the back of the occupant is restricted by the backrest of the seat, or the knees hit the dashboard, while the occupants remains within the seated position. In TW, there is no restriction to neither of these situations, so using those load limits for indirect fractures, causes an unrealistic situation. Instead, and just for further comparison, the limit of the authors who performed essays with direct pelvic front load, may be used to compare with the contact force in x-axis (criterion #1 from table 2.8). A much more reliable data is provided in table 2.9, where the loads during the essays where always applied laterally to the pelvis and directly on the cadavers test. It seems in this case to reproduce fairly the impact forces associated with TW accidents. From table 2.9 it may be defined a criterion, where in case the contact force F_y is above 10 kN (for male and 4.6 kN for female) an AIS above 2 is expected with multiple fractures. If this load exceeds the upper value of 11.6 kN for male, and 8.2 kN for female, multiple fractures are expected to occur, although it shouldn't be discarded a fracture occurrence probability, if the value is already above 4.9 kN (for male, or 4.4 kN for female), since this value is reported as the lower limit for injuries. Of course these are order of magnitude values, since it depends from person to person. For comparison, Kuppa (2004), brought together several works on mechanical properties of pelvic bones, obtained in cadaver tests. One of the criteria is to get the acetabular and iliac wing total horizontal force and compare the result with Kuppa (2004) thresholds of probability of fractures occurrence. These results correspond to the values within the graph in figure 2.4.

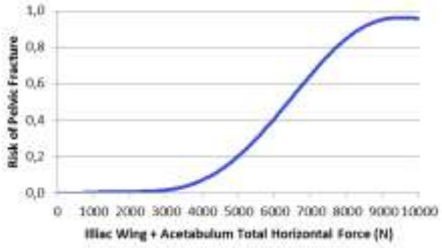


Figure 2.4 - Risk of AIS>2 pelvic fracture as a function of iliac wing and acetabular force [adapted from Kuppa (2004)].

The other criterion is, using the applied force on pubic symphysis, determine the probability of lesions occurrence with severity above AIS 2 and 3. The results correspond to the graph of figure 2.5.

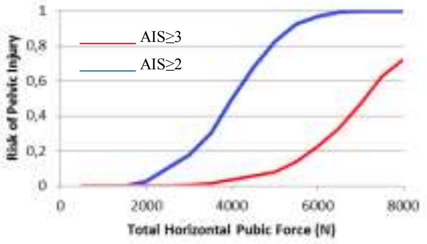


Figure 2.5 - Graphic representing the pelvic injury risk as a function of the horizontal pubic symphysis force measured [adapted from Kuppa (2004)].

In case of the PC-Crash^{TM} available results, both the comparisons can be made, using the total horizontal force in the pelvic segment, which is of course the value in the center of gravity and not located in any specific region. In a rough comparison, the AIS estimation can be done using the forces in x-y plane and compared with the clinical and/or medico-legal autopsy reports to determine the AIS correspondence. The other is a more fine approach which leads to the probability of fractures occurrence.

2.1.6 Lower Extremities Injuries

Like in pelvis, the occurrence of lesions in lower extremities (thighs, knees, lower legs and foots), are related with fractures. The major areas of legs exposed to fractures are long bones, femur, tibia and fibula. With particular attention to the bones of the legs, fracture patterns are differentiated depending on the loading conditions that motivate the fracture, *i.e*, the injury mechanism. There are four possible types of fracture mechanisms, the direct loading, indirect loading, repetitive loading and penetration. Except for repetitive loading, either of the typed may be presented in lower extremities injuries resulted from TW vehicle accidents.

Levine (2002) reports several load limits for lower extremities. These values may be used within PC-Crash^{TM}, data by comparison of maximum forces. Table 2.10 summarizes the mechanical strength as reported by Levine (2002).

Table 2.10 - Mechanical strength of bones of lower limbs.

	Femur		Tibia		Fibula	
	Male	Female	Male	Female	Male	Female
Torque (Nm)	175	136	89	56	9	10
Bending (kN)	3.92	2.58	3.36	2.24	0.44	0.30
Average Max Moment (Nm)	310	180	207	124	27	17
Compression in z-axis	7.72	7.11	10.36	7.49	0.60	0.48

The comparison of the values obtained by PC-Crash^{TM} simulations with the tables, are mainly to check for fractures probability and compare with clinical and/or medico-legal autopsy reports. It is not within this particular analysis objective to achieve a value of AIS, although this can be done, knowing that, especially in cases of TW, sometimes severe fractures can lead to high blood volume lost, which can became a life threatening, and in this case, AIS is for sure above 3. Still, usually, this does not appear as a single cause of death, so, for a first approach, fractures are the main goal. Initially the comparison with the threshold values is made considering bending, *i.e*, the resultant load within the transverse plane and compression, *i.e*, the load in z-axis.

For bending comparison with the limits, the load applied is the resultant in transverse plane, *i.e*, resultant in x-y plane. For axial loading, a comparison can be made using the risk of fracture from Tencer *et al* (2002). The risk as a function of axial load of the femur is represented in graph of figure 2.6.

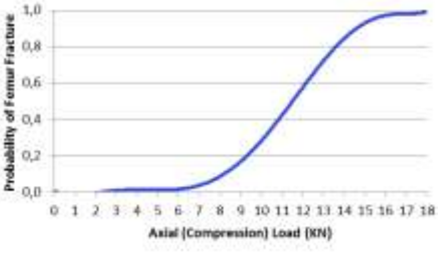


Figure 2.6 - Graphic representing the femur fracture risk as a function of the axial (compression) load [adapted from Tencer et al (2002)].

For ankle and foot deep research is currently being conducted to better understand the complex mechanisms of foot and ankle injuries. This deep analysis is not included in the present work.

2.1.7 Upper Extremities Injuries

Similarly to pelvis and legs, the injuries occurrences in upper limbs are mainly fractures. In arms, the most common are clavicle fractures which occur, for example through compression during lateral impact of the shoulder, or in falls on the outstretched arm.

As for the lower extremities, the main goal in this analysis is to compare the forces obtained using PC-Crash^{TM} with limits for failure. There aren't many studies on mechanical properties of upper extremities bones. For many years there were used many values obtain in 19th century by several authors. Probably this is motivated by relative low severity injuries in arms caused by automotive accidents. Only recently, more attention was paid due to several lesions caused mainly by airbag deployment, especially in the forearms. Schmitt *et al* (2007) compiles several results from tests performed in human cadavers, to determine the failure limits of arm and forearm. Many of those tests were performed limiting the thresholds for bending moment only. Since this is difficult to obtain in PC-Crash^{TM}, the important values are the shear forces that lead to the fractures. Table 2.11 summarizes the values obtained for humerus and forearm.

Table 2.11 - Failure tolerances for upper limbs.

Humerus		Forearm
Male	Female	All
2500 N	1700 N	1370 N

In forearm there is no separation in ulna and radius, thus above the limited value, either fracture may occur according to Begeman *et al* (1999).

2.2 Risk Factor

As stated, from the methods presented in this chapter to estimate and evaluate the injuries in each of the body segments, some of them allow obtaining a direct, or almost direct, injury scale level or AIS. Examples are head, abdomen and thorax. In these cases, the models allow a good correlation or even more, a direct calculation of an AIS value, *e.g*, thoracic compression criterion. Eventually due to a less probable life threatening, other segments such as upper and lower limbs and pelvis are not so easy to attribute an AIS level. Especially in cases of fractures occurrence, only situations where amputation happens, may be more dangerous and thus lead to life risk consequences. Since the limits for injuries in those body segments are defined by the determined ultimatum load in the limbs or pelvis, the criterion is kind of rigid when comparing the applied loads with the ultimatum limits. Of course this will estimate a certain probability for fractures to occur, but for each human being, a different limit load exists for each bone. Depending on many factor, like age, gender, race, body type, metabolism and other factors, the mechanical strength of the bones are different from one person to another [Rouhi (2012)]. Based on Hayes *et al* (2007), a definition of risk factor reveals useful for this purpose. This is a very simple definition based on the same safety factor engineers use for structures calculations. It's the ratio between the applied load and the ultimatum limit for fracture to occur as represented in equation 10.

$$\phi_{Bones} = \frac{F_{Applied}}{F_{Limit}} \qquad (10)$$

There are other ways to compare values with ultimatum loads recurring to statistics. For the purpose of this work, risk factor intents to provide a way to roughly predict if a fracture occurrence is likely or unlikely to happen, when comparing the higher load limits that a bone was exposed during the accident simulation with the limit values describe in previous sections. For ϕ_{Bones}«1, fracture occurrence is unlikely. Values of ϕ_{Bones} »1, the fracture occurrence is likely. Intermediate values of $\phi_{Bones}\approx 1$ are considered within the limit to cause injuries.

3 Results

The results obtained for the 20 case studies, refer to the global body lesions, *i.e*, life threatening for the victim and, in a deeper analysis, considering the body segments AIS separately. Moreover, an example is used to demonstrate the utility of these models in a reverse approach, *i.e*, use the victim's real injuries to optimize the computational simulation for accident reconstitution.

3.1 Global Results

Global injury results compares the victims whole body lesions for all case studies using the ISS (Injury Severity Score) predicted by the application of the models, and the estimated corresponding value based on clinical or medico-legal autopsy reports. ISS is obtained using the three body segments with AIS higher scores, according with equation 11:

$$ISS = AIS_1{}^2 + AIS_2{}^2 + AIS_3{}^2 \qquad (11)$$

Where AIS_1, AIS_2 and AIS_3 correspond to the 3 higher injury scores body segments in the victim. Table 3.1 summarizes the ISS results from the model and clinical or medico-legal autopsy reports for the case studies. For each case the correspondent percentage of mortality is included based on the ISS values [Silva (2004)]. ISS for medical results was obtained using the estimated AIS from the injuries tables.

Table 3.1 - Global injuries severity for each case study predicted by application of the models and data from clinical/medico-legal autopsy reports.

Case Study	Victim Injuries	ISS		Percent Mortality	
		Model	Medical	Model	Medical
1	Fatal	75	66	100	100
2	Fatal	48	50	60	60
3	Fatal	27	57	50	50
4	Fatal	75	75	100	100
5	Minor	4	0	0	0
6	Minor	0	1	0	0
7	Fatal	75	75	100	100
8	Fatal	75	75	100	100
9	Fatal	57	38	80	40
10	Fatal	75	75	100	100
11	Fatal	27	22	20	15
12	Fatal	75	75	100	100
13	Minor	17	9	5	0
14	Fatal	75	75	100	100
15	Fatal	75	75	100	100
16	Fatal	75	34	100	30
17	Fatal	41	41	40	40
18	Fatal	66	34	100	30
19	Fatal	75	75	100	100
20	Fatal	75	75	100	100

Considering the three accidents where just minor injuries occurred, the model and medical reports agree in the ISS and consequently in the percent mortality. In these three cases, the obtained values lead to 0% mortality which is consistent with the minor injuries on the victims. For the fatal cases, the apparent discrepancies are in cases 9, 11, 16, 17 (both with 40% mortality probability) and 18. In cases 9, 16 and 18 it is actually the model that predicts the higher death probability. This may occur due to some miss information or miss interpretation of the contents of medico-legal autopsy reports and thus leading to under evaluation on the reported lesions AIS. Since ISS uses square values, even minor differences in the injury scales may affect the result. One way to correct this situation may be to use the cause(s) of death certification results and attribute to those segments an AIS 5 or 6 in the medical report injuries scale. Also, especially in case 18, the medico-legal autopsy report is very incomplete. In case 17, both the ISS are in agreement with 40% of mortality probability. In this situation the victim was an old age male. Since the ISS does not account for age variability, the consequences of the same trauma may be very different from person to person, so in spite of already a non-negligible probability, the situation might be further compromised by the age of the victim. In case 11, once again both the results are in accordance and lead to about 20 % death probability. In fact, this victim was hospitalized during 47 days and died due to sepsis. This delayed death after the accident may be attributed to severe but not fatal injuries, resulting from the crash itself, being the direct cause of death (sepsis) complications from these severe blunts, which is in accordance with the obtained values for crash injuries ISS, for both medical and model predictions.

3.2 Body Segments Results

A more fine analysis consists on the comparison of the results obtained by the model and the clinical and/or medico-legal autopsy reports information for each of the body segments previously described in the methods.

Case studies omitted correspond to situations where no information about this body segment was available either in neither clinical nor medico-legal autopsy reports.

3.2.1 Head Injuries Results

The results for the head correspond to the higher AIS value, obtained by the criteria previously described. The bars graph from figure 3.1 makes the comparison between the head injury results of medical and model scores for each case study.

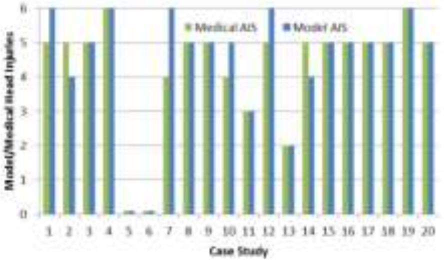


Figure 3.1- Comparison of head AIS determined by the model result and the values obtained from clinical/medico-legal autopsy reports.

From the bar in figure 3.1, besides the accurate agreement in 14 of the cases (cases 5 and 6 corresponds to medical and model AIS 0) the others are only 1 (absolute) score point away except one (case study 7), where the difference is 2 units from medico-legal autopsy report AIS 4 (severe) and model prediction AIS 6 (maximum). In all the cases where this mismatch occurs, the lower level is at least AIS 4. So, the differences found in the correspondence are qualitatively from severe to critical, or critical to maximum.

For head injury criteria, the angular acceleration (α_{Head}) criterion corresponds more often with the victim real AIS_{Head} results than the HIC. α_{Head} application lead to 14 cases where AIS matches, with additional 6 cases where the difference is one score unit. HIC leaded to seven exact matches, five with difference of 1 level and the remaining eight cases where the difference is 2 or above.

3.2.2 Neck Injuries Results

According with medical information, only in three of the 20 case studies reported lesion in the neck. In the other 16 cases, the values are actually in accordance, being the AIS less than 1, predicted by the model and corroborated by the clinical or medico-legal autopsy report. The graph from figure 3.2 illustrates the comparison between these two sources.

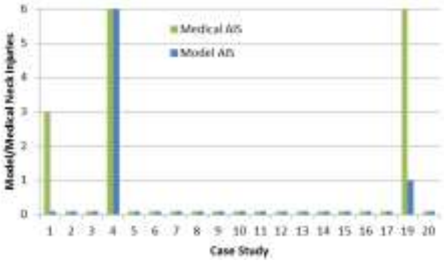


Figure 3.2 - Comparison of neck AIS determined by the model result and the values obtained from clinical/medico-legal autopsy reports.

Since in the majority of the cases both model and medical injury score levels match, this could be used to validate the N_{ij} criterion. On the other hand, for the AIS values obtained by the medico-legal autopsy reports describing lesions for this segment, only one is in accordance with the model prediction. This corresponds to a value of $N_{ij} >>1$ due to the decapitation of the victim. Since in this case this value largely overtook the threshold caused by the extreme intensity of trauma and, in the other two cases, N_{ij} didn't achieve a lower limit more than 1 in severities with AIS equal or above 3, it may lead to question the criterion, especially the lower threshold limit for injuries to occur. The only situation where this value represented a severe injury, according with the model application, was in case study 18 that N_{ij} value predicted $AIS_{Neck}=3$, but unfortunately, the medico-legal autopsy report was very incomplete regarding neck injuries, and provided only description about the head and one of the legs injuries (exposed fracture).

3.2.3 Thoracic Injuries Validation

Except for case study 18, all the others got clinical and/or medico-legal information of lesions in this body segment.

Considering the three injuries evaluations criteria described, the model injury result corresponds to the maximum AIS obtained by the different criteria. Figure 3.3 illustrates the comparison between the model and clinical/medico-legal AIS_{Thorax}.

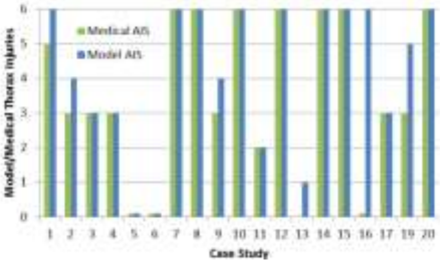


Figure 3.3 - Comparison of thorax AIS determined by the model result and the values obtained from clinical/medico-legal autopsy reports.

From the 19 cases where sufficient information was available for comparison, 13 matches were obtained with exact injuries severity score. On the other 6 cases, 4 had a difference of one unit and only in 2 cases the AIS differed from 2 or more units.

In the situations were a difference exists, the model injury prediction is above the real level (according with the clinical and medico-legal autopsy reports). In thorax, considering that the injury criteria rely on forces and/or accelerations in transverse plane, it is not valid to make comparisons between the criteria, since these depends on the type of impact, mainly frontal or lateral.

3.2.4 Abdominal Injuries Validation

Only one injury criterion was used and the correspondence with the victim's clinical or medico-legal autopsy reports, matched accurately in 12 cases (from 19 usable). In the other seven cases, three differ from 1 unit and the other four from to 2 or 3 units. The bar from figure 3.4 illustrates this comparison.

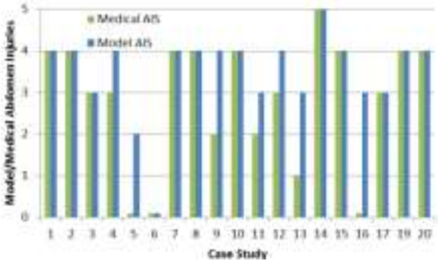


Figure 3.4 - Comparison of abdomen AIS determined by the model result and the values obtained from clinical/medico-legal autopsy reports.

From the graph of figure 3.4, the discrepancies between the model injury prediction and the clinical/medico-legal autopsy reports are in all cases an over estimation by the model of the injury score level. It must be kept in mind that the abdominal injury criterion uses an intermediate load between thorax and hip, since PC-Crash^{TM} doesn't calculate variables in this segment. Still, except for case study 16, this enables a good approach for the observed injuries and provides a good estimation of the life threatening of the victims motivated by abdominal lesions. As it can be observed in the graph, the cases where major differences occurred between the model and the actual victim's lesions are the ones corresponding to less severe abdominal lesions, *i.e*, AIS 1 and AIS 2. For all the situations where victims suffered abdominal injuries of AIS≥3 (13 cases), almost a complete match is observed with just 2 cases differing from 1 unit (case studies 4 and 12) both of them with clinical or medico-legal autopsy of AIS 3 (severe) and model prediction of AIS 4 (serious).

3.2.5 Pelvic Injuries Validation

Except for major disruption or amputation, pelvic injuries severities are AIS≤3 and this refers mainly to fractures occurrence. The fractures occurrence criterion estimation relies on a comparison of loads and accelerations obtained with average upper limiting values. The results obtained for 17 of available pelvic information case studies are represented in graph of figure 3.5.

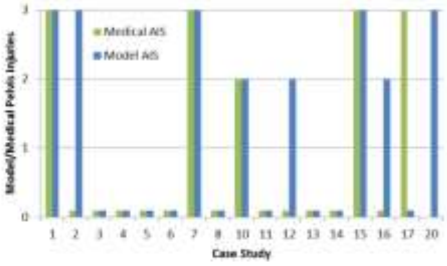


Figure 3.5 - Comparison of pelvis AIS determined by the model result and the values obtained from clinical/medico-legal autopsy reports.

In 12 of the 17 cases with pelvic lesions information, a complete correspondence was achieved. On the other 5 cases differences of 2 and 3 units were observed.

In the cases where the victims suffered only minor injuries, no pelvic lesions were mentioned in the clinical reports. This is in accordance with the model predictions. Situations where a mismatch occurred are case studies 2, 12, 16, 17 and 20. Except for case 17, all the others refer to very young victims, being the oldest 28 years old. As mentioned, the limiting values for fractures to occur are average values, which do not take into account the age of the victim. Since it is expectable that young people have higher mechanical strength in bones than older people [Diab *et al* (2006), George and Vashishth (2006)], it may be expectable that fractures occur with a load application above the model's threshold. In fact, for those situations the model over predicted the fracture occurrence, while the medico-legal autopsy reports didn't mentioned any lesions. Analyzing the risk factor for those cases, cases 2 and 16 are $\phi_{Pelvis}=1$, *i.e*, the fracture occurrence risk is in the boundary limit. For cases 12 and 20 the risk factor are respectively 2 and 3, but, once again these are the younger victims, with 20 and 21 years old respectively, and thus, the same explanation may be given. Corroborating this theory, but in the opposite direction is the case 17. In this accident no injuries are predictable by the model and the risk factor is $0.5<\phi_{Pelvis}<1$, but in this case, the victim was a 70 years old male with a less dense skeleton and, in accordance, the medico-legal autopsy report mentioned pelvic fractures.

3.2.6 Lower Extremities Injuries Validation

Lower extremities injuries follow the same fundamental as for pelvis. This estimation lies under the principles of comparison between the estimated loads acting within the thighs and legs, and some reference values for upper ultimate limits for bending and compression. In the PC-Crash^{TM} multibody simulations it is very difficult to validate the upper and lower limbs impacts to reproduce exactly the accident dynamics. For the injuries severity evaluation in lower extremities, every time at least one of the four risk factors reached a critical value, the corresponding AIS for fracture was attributed in the segment as a whole. The lower extremities segment AIS obtained is compiled in graph from figure 3.6.

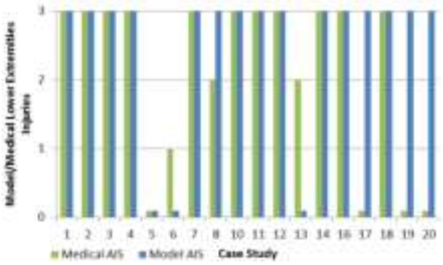


Figure 3.6 - Comparison of lower extremities AIS determined by the model result and the values obtained from clinical/medico-legal autopsy reports.

For the 20 case of studies, only 18 have medical records on this segment. Since the analysis reports to upper and lower legs, the possible injuries are AIS 2 or AIS 3 corresponding respectively to fractures in lower (tibia and fibula) and upper leg (femur).

12 matches were obtained for fractures in lower limbs (AIS 2 and AIS 3). For the cases with victim's minor injuries there is a complete correspondence in one case and a difference in one unit for the other two (cases 8 and 13). For case 8, the victim suffered

injuries on the left knee and a fracture on the right foot. Even given AIS 1 to lower extremities, this couldn't be predicted by the model for two reasons. First, since the possible detection is for fractures in upper and lower leg, the minimum model threshold is AIS 2. Secondly, the contact forces for comparison obtained by PC-Crash^{TM} are applied in the center of gravity for upper and lower legs, *i.e*, near the center of gravity of femur and tibia and not on the knee or foot. So, these results are in accordance with the observed victim injuries, *i.e*, saying that $AIS_{Medical}$ is 1, is corroborated by $AIS_{Model} \leq 2$. In case 13 the lower limbs, $AIS_{LE}=2$ is attributed to a fracture on left tibia according with AIS tables. In spite of the difference between the model and the medical report, the risk factor for fractures obtained is inferior to 1, but the highest is 0.9, which is a suitable value for fractures to occur. So, in this case, the best way to evaluate the lesions isn't to attribute a AIS values for the model, but to say that the predictive values is confined to the upper limit of 3, *i.e*, $AIS_{Model} \leq 3$ and thus it provides a fair approach. Differences of 3 score units were obtained in cases 17, 19 and 20. Victims from cases 19 and 20 were young male adults with respectively 20 and 21 years old. The risk factors for lower extremities fractures obtained for case 19, are in the range from 1.5 to 2.6 and for case 20, this value varies from 0.3 to 6.7. A similar situation already explained for the pelvic injuries (where case 20 was included) may have happened here, which stands that, since the victims were very young, the mechanical strength of the bones was higher than the model's threshold. Case 17 was already explored in the previously section: the fractures were predictable either by the model or the age risk factor of the victim. The only injuries reported in the medico-legal autopsy reports are excoriations on the legs. Since many lesions suitable to directly cause the death were already reported, it could happen that the medico-legal exam on the extremities was somewhat abbreviated, or the computation simulation produced unrealistic results in this body region.

3.2.7 Upper Extremities Injuries Validation

Upper limbs injuries evaluation is unfeasible using AIS scale. Taking the advantage that PC-Crash^{TM} enables to obtain the contact forces results in these segments, the only upper limbs comparison for the case studies is the fractures occurrence probability with the clinical and medico-legal autopsy reports information, which apart from an AIS evaluation, in practice is the same as done for pelvis and lower extremities. Although obtained for upper (arm) and lower (forearm) left and right limbs, the criterion is solely based on the risk factor. If at least one of the limbs presents a risk factor above one, the model assumes the occurrence of fracture(s) in the upper limbs. For fatal cases only, since once again this is a segment with secondary importance for the forensic pathologist, when certifying the direct cause of death, the cases where the medico-legal report's record of external observations reported upper limbs excoriations and no further internal information, were considered as actual occurrence of fractures (case of study 1 and 17). From the total 20 cases, 17 had information available for this body segment. Table 3.2 resumes the cases with the fractures occurrence predicted by the model and reported by the clinical and/or medico-legal autopsy report. Last column indicates the correspondence between the two sources.

Table 3.2 - Case studies upper extremities fractures occurrence summary and comparison with the clinical/medico-legal autopsy reports.

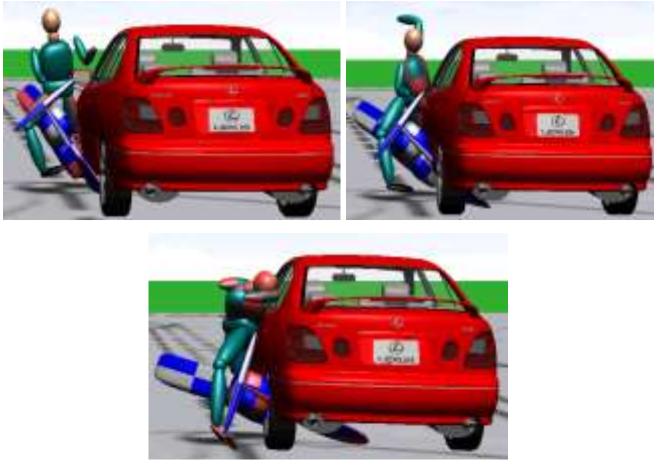
Case Study	**Injuries**	**Fractures /Excoriations Occurrence**		
		Model Prediction	Medical/Forensic Report	Match
1	Fatal	Fractures	Excoriations	Yes
2	Fatal	Fractures	Fractures	Yes
3	Fatal	Fractures	Fractures	Yes
4	Fatal	Fractures	Fractures	Yes
5	Minor	No Fractures	No Fractures	Yes
6	Minor	No Fractures	No Fractures	Yes
7	Fatal	Fractures	No Fractures	No
8	Fatal	Fractures	Fractures	Yes
10	Fatal	Fractures	Fractures	Yes
11	Fatal	Fractures	Fractures	Yes
12	Fatal	Fractures	Fractures	Yes
13	Minor	Fractures	Fractures	Yes
15	Fatal	Fractures	Fractures	Yes
16	Fatal	Fractures	No Fractures	No
17	Fatal	Fractures	Excoriations	Yes
19	Fatal	Fractures	Fractures	Yes
20	Fatal	Fractures	Fractures	Yes

There is a good correspondence between the two sources. Only in two cases the model predicted occurrence of upper limbs fractures and was not corroborated by the clinical or medico-legal autopsy report.

3.2.8 Example of Accident Reconstitution Optimization

While performing the simulations of the accidents, several inputs are used and also methods and procedures for the optimization of the results [ACEM (2003)]. One way to optimize these results is to perform a simulation and use the injuries criteria to obtain the injury score in a certain body segment. When comparing the result using the models previously described with the clinical or medico-legal autopsy data, if a major mismatch is observed, it is feasible to change the parameters in order to obtain a more correct injury score, *i.e*, in accordance with the medical data, by changing simulation parameters and thus obtain more coherency with the accident real situation. This example refers to case study 3. In the first computation simulation of this case, all the body segments injury level agreed (between the model and medico-legal data) except for the head, where the lesions were the direct cause of death determination, according with the medico-legal autopsy report.

Most probably, the non-agreement of this segment was related with the actual crash's collision itself. In this accident the motorcycle and the car collided tangentially in the lateral front left side. The simulation, although cinematically validated (based on the final positions given by the authorities report), dynamically, big changes may occur with just slight differences in the input parameters. For example, if no head contact exists with the car during the first impact, the head impact on the ground, resultant from the fall of the motorcycle driver, may not produce enough contact forces to cause fatal injuries, since the hi intensity contact forces or accelerations occurs in the first impact and not in the subsequent fall. In this case, the medico-legal autopsy report leads to head injuries of AIS 5, while the model predicts maximum AIS 2, due to the angular acceleration, and AIS 1 due to HIC, with a skull fracture probability less than 10%. So, clearly, in this simulation, head impacts didn't occur in the first motorcycle driver body contact. In this case, changes in the multibody position of the motorcycle driver (typical bank angles – a common characteristic in evasive maneuvers) dictates if the head of the victim hits the front of the car in the first body impact or not. In this simulation the motorcycle occupant hits the front lateral section of the car with the torso and during a second impact the head hits the left lateral. This first simulation sequence is illustrated in figures 3.7 to 3.9.



Figures 3.7, 3.8 and 3.9 – Simulation sequence of the accident with no head contact in initial impact (squares indicate body segments contact).

As it can be observed from the sequence, the motorcycle driver's lower left leg was stuck between the car and the motorcycle leading to torso impact and then head impact both on the left lateral side of the car (color change from continuous to squares indicates body contact). The lower left leg stuck is corroborated by the medico-legal autopsy report findings and the accident pictures, since it was crushed and amputated below the ankle.

By changing the bank and inclination of the motorcycle driver, while leaving all the other parameters unchanged, a new simulation is obtained and the first impact is represented by figures 3.10 and 3.11.

Figures 3.10 and 3.11 - New simulation sequence of the accident with head contact in initial impact.

As observed in figures 3.10 and 3.11 no major changes exist in the simulation except the torso head and neck of the motorcycle driver contacts. Due to the different bank from previous simulation, the first impact of the head occurred in the left front of the car windshield. This is also corroborated by a local picture taken in the accident scene where it can be observed the broken windshield and the left frontal windshield a pillar with impact evidences in figure 3.12.

Figure 3.12 - Broken windshield on the left and impact dents (red circles) on the left a pillar.

In this optimization simulation, the injuries on the head predicted by the model correspond to 5+ *i.e*, $5<AIS_{Head}<6$ and thus in accordance with the medico-legal autopsy report head injury level. Also, the new skull fracture probability is above 90% which also corresponds to the skull fractures reported by the forensic pathologist. Since cinematically the second simulation is still valid, given the correspondence between the predictable and the observed injuries, a stronger validation on the accident reconstruction is achieved, based on the body injuries prediction models.

4 Discussion

The global injury results from the model fit the analyzed case studies results, which make it a good indicator for the application in these methods in order to a global prediction injuries, *i.e*, using the simulation to attribute a life threatening probability to the TW occupant.

For head injuries, it can be assumed that these are suitable to obtain expectable TW crash victims head lesions, based on the data from PC-Crash^{TM} simulations. Considering both HIC and α_{Head}, the angular acceleration seems to be more appropriate. However, since computationally the HIC is not an expensive calculation criterion, an optimization is achieved if both criteria are used and the upper level considered as the model injury prediction. This is supported by the case studies 4 and 19 where α_{Head} mismatched (by 1 unit) and HIC fits the correct injury level. If a case occurs where simple calculations are mandatory and a rapid estimation on the head lesions required, then α_{Head} is most probably enough for a good approach, associated with the calculation simplicity since it relies on just a maximization of the PC-Crash^{TM} results of angular acceleration and/or angular velocity of the head. One other validation possibility is for cases where α_{Head} and HIC AIS prediction values disagrees for more than 1 score unit, to use α_{Head} criterion.

For neck injuries, although there is a very interesting correlation and correspondence between the predicted by the application of the models and the ones observed in clinical and/or medico-legal autopsy reports, this is mainly due to the absence of those lesions. This can only be validated by increasing the size of the sample and of course, include as much as possible cases where neck injuries occurred with differences in the injury score.

The methods for thoracic injuries presented seems to provide a quite reasonable approach relying on the correspondence on the majority of the case studies and the correct tendency of the cases where the difference was just one unit. There is just one mismatch (case study 16) where the model predicts $AIS_{Thorax}=6$, while the report stands $AIS_{Thorax}=0$. This may be due to a simulation parameter or, since this was a fatal victim and according with the forensic report the ISS gives a mortality percent of 30%, while the models predicts 100%, there is perhaps an omitted information on the report, or a misinterpretation on the medico-legal autopsy report information.

Abdominal lesions criterion suggests being a good indicator, especially in cases of serious injuries. Once again, a full validation process requires more case studies to observe the corresponding values, and check if the mismatch situations are still over estimated by the model.

Pelvic fractures predictive model offers a good tool for pelvic injuries estimation using PC-Crash^{TM} data, but some improves should be made, especially a procedure that allows the criterion application with some capability of change the fracture upper threshold limits in accordance with the victim's age.

Apart from case 17, the lower extremities criterion, based on upper and lower legs fractures occurrence, reveals a good approach for estimation, but these lesions are secondary, when compared with other body segments, for life threat risk computation. Still, if a rough order of injuries score is required in this segment, in accidents where no amputation occurred, this method enables to create an upper boundary that limits the AIS to less than 3, if lower risk factors are obtained, and in these cases, values of AIS1 and AIS 2 from clinical and/or medico-legal autopsy reports are included, and AIS 3 for higher values of risk factors. By using this approach, an initial complete match would be obtained for 15 case studies.

Independently of the possible sources of discrepancies, like age, and the need to run more simulations including cases of victims with less severe injuries, upper extremities injury criterion can be considered a good method at least for rough estimation if upper limbs lesions are expected in an accident.

The selection of case studies used in this work was carefully made in order to get as much as possible differences between the accidents conditions. These differences refer to TW (motorcycle and respective classification, moped and bicycle), occupant, impact and victims injuries (slight and fatal). This variability of inputs enable a more relevant real world validation, eliminating at least possible coincidences of application or hypothetic good results tendency in very specific particular conditions.

5 Conclusions

The major goal of this work was successfully achieved by validation of injuries criteria on TW occupants, obtained by models applied to road accidents reconstitution.

The application of the injuries criteria for the body segments may dictate which parts were more severely affected by the accident injuries and for each one, it can predict the respective injuries level in an AIS scale.

The segments where more reliable results were achieve are, head, neck, thorax, abdomen and pelvis. These correspond to the more critical regions within the body considering the overall life threat point of view.

Pelvis, upper and lower extremities criteria are based on fractures occurrence risk factor. These ultimate limits differ from person to person, with no other input factor, such as the age of the victim, this becomes highly inaccurate. Still, it is a good method to predict the fractures occurrence, especially if a high (risk factor) value (»1) is obtained. However, these type of injuries, although interesting for accidents analysis purpose applications, usually are “peripheral” injuries with a secondary importance from the overall survival of the victim when compared with the other body segments.

The methodology presented in this work enables to apply the opposite procedure, *i.e*, to optimize the accidents simulations based on the victims clinical and/or medico-legal autopsy reports, by changing the simulation parameters in order to make a better adjustment between the observed injuries severity score and the score predicted by the simulations results using the models.

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