THE BIOMECHANICS AND PATHOGENESIS OF SEAT BELT SYNDROME: LITERATURE REVIEW

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ABSTRACT

BACKGROUND: Seatbelts are the most effective means of providing occupant protection in a vehicular accident. This works by two mechanisms; by preventing ejection from the vehicle which has been reported to be the leading cause of both injury and death in accidents. Ejection converts the passenger into a "Passenger missile" and thrown out of the vehicle on impact against some stationary objects outside the vehicle – trees, earth, Pillars, culverts, and even on innocent by-standers!
Also, ejected passengers can suffer roll-over injuries if the vehicle tumbles over and rolls over and/or crushes the ejected passenger! [(1)] Seat belts prevent compression injuries, by deploying Airbags. In 70% of collisions, Seatbelts trigger off the deployment of air bags. These air bags restrain the occupant from being flung about in the vehicle and making contact with the vehicular panels like the steering wheel and other environmental surfaces in the vehicle - especially in frontal (or head-on) collisions The airbags thus deployed prevent subsequent compression between the patient's organs and some of these framework thus preventing catastrophic compression/blunt injuries. [(2)]
Maximum protection is therefore achieved by the simultaneous use of seatbelts and airbags and this combination has been shown to reduce both the severity and fatality of motor vehicular injuries.[(3)]

AIM: To do an extensive literature search looking for an explanation of how the seat belt, a seemingly safe/protective device can become a weapon of severe and at times very fatal injury.

METHODOLOGY: Literature search about "Mechanism of Seat-belt syndrome" was done via websites like "*Netting the evidence*" website:www.shef.ac.uk/scharr/ir/netting which gave us a comprehensive list of internet resources and also sites for virtual library. We also visited the Cochraine library via their website www.the*cochrainelibrary*.com which supplied us with the database of Abstracts and Reviews. We also looked at *Systematic Review and Controlled trials* of high impact collisions using robots, baboons and other mammals. We also used the *Pubmed Advanced Search* tool looking for the "Mechanism of Seat belt syndromes"

RESULTS: The relative risk taken by an occupant without a seat-belt is 70% higher than that of a belted occupant. Therefore seatbelts, properly installed and properly worn, offers the best protection for the automotive occupant during impact.

CONCLUSION: Seat-belts do not prevent accidents; they only work when accidents have occurred. The simultaneous action of seat-belts and air-bags have shown to reduce both the severity and fatality of motor vehicular injuries.

KEY WORDS: Seat Belt; Seatbelt Sign; Visceral Injury, Chance Fracture.

NigerJmed2019: 323- 330

INTRODUCTION

From a number of research and accident investigations, it has been conclusively demonstrated that seat belt is the single most effective way of providing occupant protection in a vehicular accident by reducing both the severity and fatality of an injury.[1]
Seat belts however do not prevent the accidents: seat belts do not help a car with failed brakes to stop; seat belts do not control the speed of a car; seat belts do not control the recklessness of a drunk-driver etc.

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Seat belts only work when an accident has occurred to reduce the severity of the injury. It does this by two mechanisms:-

(i) **Preventing ejection.** Ejection converts the occupant into a "passenger missile" and has been shown to be the leading cause of both injury and death in accidents.
(ii) Seat belts also work by Restraining the occupant from being flung about within the vehicle during an impact sequence. This prevents the passenger from colliding with the vehicular panels like the steering wheel, dash board and other hard interior surfaces of the vehicular environment during the impact - especially in frontal (or

head-on) collisions. In 70% of cases, this has been shown to be the main mechanism by which seat belts reduce/prevent fatality during a vehicular accident.

Airbags on the other hand, when deployed, prevent subsequent compression between the patient's organs and some of the framework which would have otherwise produced catastrophic compression/blunt injuries.[2] Air bags provide no protection in roll-over collisions, lateral collisions, rear impacts and in second crashes since they cannot be deployed twice.

However, maximum protection is achieved by the simultaneous use of seatbelts and airbags and this combination has been shown to reduce both the severity and fatality of motor vehicular injuries.[3]

This paper is principally to review the biomechanics and pathogenesis of "restraint system injuries" and not those of airbags and to proffer the mechanism and pathogenesis of these "Restraint System Injuries" and thus caution as to how to use them properly.

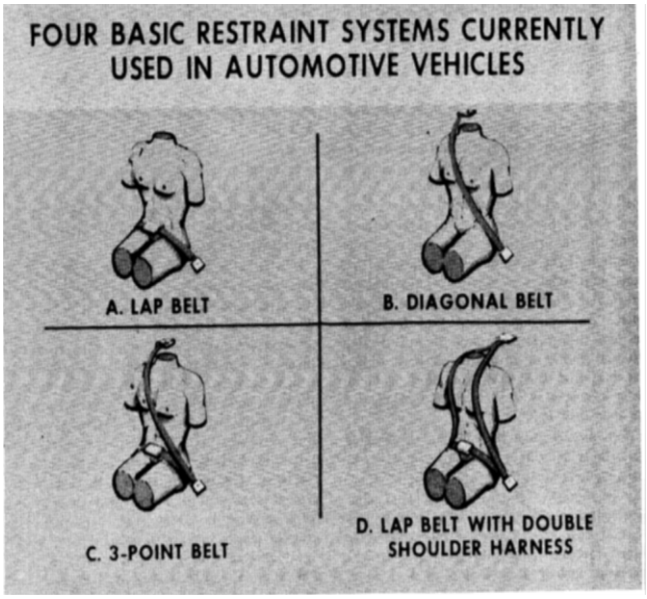
There are four principal configurations of seat belts in automotive use:

(i) **The lap belt**- which is the single belt that is supposed to lie across the anterior aspect of the heavy pelvic bones and structures

(ii) The single **diagonal belt**.

(iii) The three point or combination of lap and diagonal (**Type II seat-belt**)

(iv) **The double shoulder harness** or upper torso restraint. (see fig.1)



[Courtesy: Highway Safety Institute; Ann Arbor. Michigan USA]

Therefore, "Seat belt" by description, refers to any combination of 'lap' and 'upper-torso' restraint.[4]

Lap belts alone reduce 20-35% of injuries while diagonal belts reduce 65-80% of the injuries[5]

It is ironical that this protective device has been shown to be responsible for distinctive injury patterns collectively referred to as "Seat Belt Syndrome" [6]

DEFINITIONS.

1. THE SEAT BELT SYNDROME

'Seat Belt Syndrome' consists of a triad of:

(i) Superficial skin bruises - like Abdominal Wall Ecchymoses (AWE)

(ii) Visceral Injuries

(iii) Musculo-Skeletal Injuries.

In the incomplete or partial seat belt syndrome there is absence of any of the components of the triad - like absent external abdominal wall trauma (AWE) but presence of other internal injuries.[7] etc.

2. The **seat-belt sign** is a superficial/B anterior skin injury caused by seat belt use.

MECHANISMS/BIOMECHANICS OF INJURY

A. Superficial skin bruises.

Superficial skin bruises (like the abdominal wall ecchymosis) are actually welts drawn across the torso. They constitute the seat belt sign. They are as a result of skin contusions along the belt-line[8]. [Fig 2.]

Fig. 2 [Courtsey: www.regionstrauma.org]

They are commonly seen in places like the lower abdomen below the umbilicus, mid-abdominal wall over the anterior superior iliac spine, or even anterior chest. They present as bruising, laceration, avulsion or other signs of direct trauma to the skin in the area of the "lap portion" of the belt. Some can be so severe and so deep that, in some side impacts, the diagonal belts have caused the decapitation of occupants on impact!![9]

The presence of a seat belt mark (or sign) has a 4 times likelihood of chest injury and an 8 times (65%) likelihood of abdominal injury than without this sign (8%).[10]

A. The Visceral injuries.

Any internal organ may be injured by seat belt but it depends on 2 factors:

(i) The mechanism of the injury and

(ii) Position of the belt.

The mechanism of the injury.

In the Restraint systems, the pattern of the injury depends on Direction and magnitude of the force, body orientation, time duration, seat pitch.

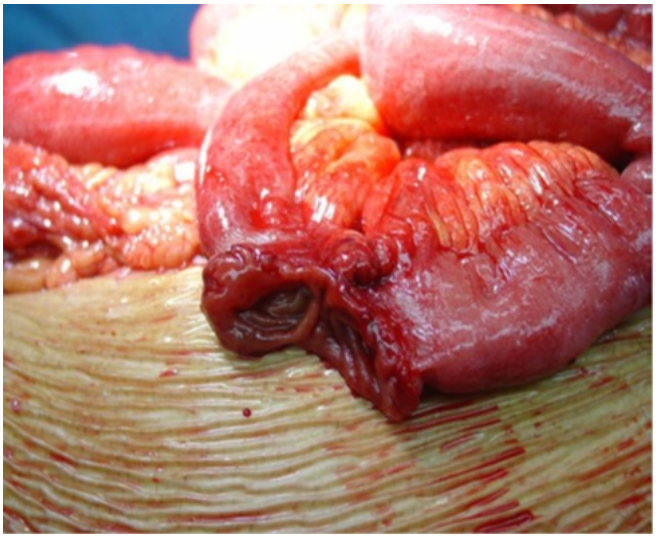
The mechanism of the injury may be direct violence, torsion, shearing force, entrapment or a combination of factors.

As the kinetic energy transfer during a collision is halted by the restraint device, forces are applied to the occupant which give rise to injury. Spectrum of injuries may range from hollow visceral blow-outs, mesenteric tears etc. The small bowel with its mesentery appear to be the most vulnerable to direct force, whereas the retroperitoneal organs like the duodenum and pancreas are damaged by shearing force produced by the body flexion. This shearing force is generated as a result of the organs, continuously moving at the same speed of the car although the car is decelerating following brake application and impact.

The shearing force can result into trivial mesenteric tears or to serious bleeding.[11]

Intra-abdominal consequences – like injury to the terminal ileum and caecum (bruising, perforation etc) is caused by crushing of the terminal ileum on the right iliac crest of the pelvis by the lap belt;[12]
[Fig 3]

Figure 3: Ileal perforation



[Courtesy www.sciencedirect.com]

Perforation of the small bowel or colon is usually a result of direct violence to a distended loop or entrapment of a short segment to form a closed loop obstruction.[13]

Jejunal perforations – especially upper jejunum; and, rarely, rupture of the sigmoid colon are due to sudden compression of the intestine between the seat belt buckle and the vertebral column[14] and this also produces contused bladder and kidney. The postulation is that the perforation/disruption occurs at the interface where the head of the mass of food had progressed at the time of impact.[15]

In cases of multiple lacerations of the mesenteric attachments of the small bowel; traumatic amputation of the omentum ocur and are due to the jerking of loose belts during impact allowing the lap belts and buckle to go up the abdomen with a sheering force – tearing the mesentery and bowel along its course as well as producing the contusion of the anterior abdominal wall.[16]

Splenic injuries like severely ruptured spleen and ruptured pancreas and duodenum are due to direct violence from improperly applied seat belt.[17]

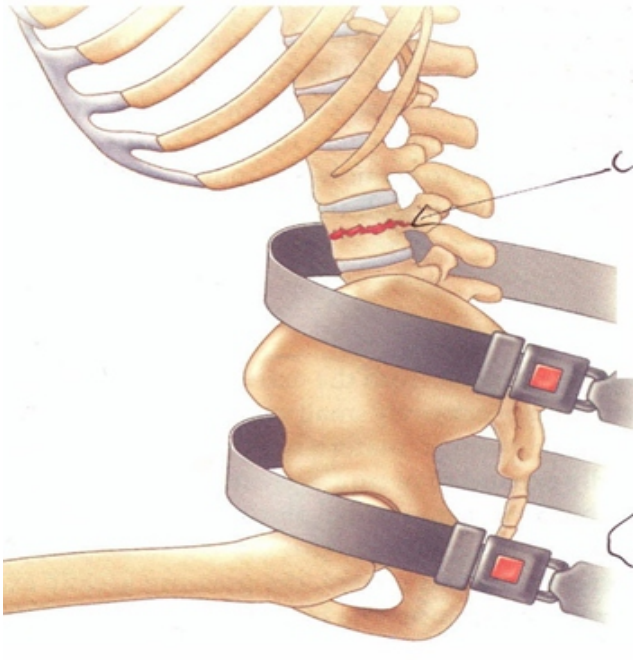
Neurological injuries like concussions, nasal fracture, lacerations of the cheek ; Cardio-vascular injuries like thoracic aortic ruptures; the division of the ilio-caecal artery and endocrine organ trauma are all due to the snubbing action of the lap belt with a forced flexion of the torso.

Osseous Injuries

Osseous seat-belt injuries include the entire class of seat-belt-related injuries to the spine - now commonly referred to as "Chance fracture". Chance fracture is therefore a hyper-extension/hyperflexion horizontal fracture of the vertebral body, spine and transverse process of the (cervical) spine (**the Chance injuries)** described by Chance in 1948[18,19;]

The mechanism of Chance injuries affecting the lumbar spine is that there is a forced flexion and hyperflexion of the torso over the immobilised lower lumber spine around the lap-belt acting as a fulcrum thus subjecting the vertebrae to tension and distraction[20] resulting in a tension force across the posterior elements of the vertebrae. There is disruption of the posterior elements of the lumbar spino-osseous and ligamentous tissues with a longitudinal separation of the disrupted elements. There is usually no or minimal compression of the vertebral body and no or minimal forward displacement of the superior vertebrae and no or minimal lateral displacement between L1 and L3 vertebrae. The tissue failure may ocur through the posterior elements of the vertebra body producing a "**bony chance**", or through the ligamentous tissue and intervertebral disc producing a "**soft tissue chance**". Compression by the restraint itself, causes the other (internal) components of the syndrome.[21] [Fig 4]

Figure 4: Chance Fracture



Courtesy: Advanced Trauma Life Support (8th Edition)

Other osseous injuries include Pelvic injuries which consist of Lumbar spine injuries;
Contusions or soreness over the iliac crests, lumbar muscle sprains or strains
Left anterior fractures of 7th, 8th ribs – attributable to improper looseness and high position of the lap-belt (i.e across the abdomen and lower rib cage – probably due to heavy panniculus or habitus. Such a badly worn belt transmits the impact force to the intra-peritoneal organs rather than the heavy pelvic bone[22]
Fractures of the Vertebrae ocur via "Tension-type" mechanisms:

- Compression fractures of the lumbar vertebrae occur when the passenger "jacknifes" over the lap belt[23].
- Transverse fractures of the vertebral body, including fracture of the pedicles, transverse processes, and lamina of (especially) the third lumbar vertebral with subluxation i.e hyper-extension/flexion or "whiplash" injuries of the 4th lumbar, occur following a high placement of the seat (lap) belt or a loosened lap-belt which then allows the belt to act as a fulcrum and literally "splits apart the vertebral body – similar to breaking a stick over one's knee![24]
- The snubbing action of the seat belt during the accident can also cause a fracture of the transverse process and subluxation of the fourth lumbar vertebra over the fifth.

Fracture of the Left elbow which is usually caused by a loose diagonal belt – as explained in the mechanism of action of diagonal belts below.

In pregnancy

Traumatic rupture of the pregnant uterus occurs on account of the external force of the seat belt.
Avulsion of the uterine musculature at the site of the seat belt impact do ocur. This is because the force of the belt at the anterior uterine wall is transmitted to the foetus – which may actually be fatally ejected from the uterus – but the mother's life can be saved!!![25].
Dyer, a traumatologist commented that:
"There is no question that seat belt may cost the life of the foetus but there is also no question that the same seat belt can save the mother's life".[26]

When the lap-belt is worn wrongly - like high placement of the belt over the fundus, a vertical

force will cause a jolt and a partial or complete placental separation, deep laceration on the posterior aspect of the uterus and extensive "belt contusion". So, a high placement of the lap belt for any reason, contributes to the injuries.

Role of Belt Positioning.

Impact tests have shown that variables like restraint system, direction and magnitude of force, body orientation, time duration, pitch and other factors even if they may not appear extensive, are contributors to the injuries of the seat belt syndrome[27]

Lap Belts.

In Lap belts, attachment (anchorage or tie-down) is to the floor of both sides of the seat – normally allowing a belt angle of about 40^0 to 60^0 to the horizontal.

Correctly mounted and worn, Lap belts are positioned over the pelvis at the level of the anterior superior iliac spines. In this position, it provides support for the body's sturdiest framework – the pelvic girdle. Thus it has the advantage of allowing the head and thorax to swing free in a "jack-knife" motion during impact – while exerting its pressure on the well-protected pelvic girdle.[28]

So the use of a lap belt only, while generally preventing ejection, can still allow the upper body, (the head and neck) freedom to move during deceleration and striking surrounding structures.

Without the lap-belts, occupants can strike their heads against the wind shield, impacting the face and chest against the steering wheel and dashboard, hitting the unrestrained body against roof and doors, or ejection of the victim from the car!

Intra abdominal injuries are related to improperly worn (i.e. high and/or loose) lap belts and ocur in the plane of the lap portion of the belt. This is due to a shearing force transmitted directly between the lap belt and the spine. These result in the belt contusion that manifests as abdominal wall ecchymosis – a transverse contusion across the lower abdomen. They are also the causes of haemorrhage of the head of pancreas, bilateral haemorrhages of the kidneys, pelvis and uterine sub-serosal congestion. Rupture of major neck vessels, bilateral peri-renal haemorrhages, haemorrhage of the anterior bladder wall; avulsion of the abdominal walls at the pubis, transverse lacerations of the buttocks, contusions, sub-serosal haemorrhages of the neck of the uterus. Ruptured uterus, peritoneal tear of the proximal rectum.

The intra abdominal injuries usually sustained are primarily solid viscera (especially liver and spleen) more than hollow viscera.

It is the lap-component of the three point belt system that causes pancreatic haemorrhage (intra-acinar and intra-lobular haemorrhages) and also retro-peritoneal and intra lobular haemorrhage from impact impingement of the lap-belt. The intra abdominal forces are sufficient enough not only to rupture the capillary bed but also to break the more delicate radicules of the intralobular ducts – formed only by the centro-acinous cells, releasing and activating pancreatic enzymes.

The Diagonal Belts

The diagonal (also called the bandolier) belts are anchored to the B-post pillar or above the rear door, and extends across the shoulder and chest on the outboard side where it is anchored to the floor.

Thus the diagonal belt provides support to the torso – from the hip on the one side to the opposite side of the shoulder joint.

During a collision, energy is transferred from the shoulder component to the occupant's neck and other intra thoracic structures.

Thus if there is no lap belt (horizontal) support across the anterior pelvic area, at impact, unless stopped by the occupant striking the instrument panel or any part of the vehicle itself, there will be a swinging forward and/or rotating out of the diagonal belt on impact and critical injuries to the neck and other internal organs when the wearer slides down ("submarines").

When diagonal belts are worn incorrectly – i.e. under both arms, injuries of the thorax are particularly prevalent. Such a position does not restrain the occupant who is now flung from the seat –hanging himself as rotation ocurs about the inferior axis of the belt. If the system truly does not have a lap-belt, the rotation causes the lower portion of the body to pitch up about the belt so that at one point in the impact sequence, the body is horizontal in the seat then rotated so that the head is on the seat and the feet straight up in the air vertically!! Then finally it comes to rest outside the belt at the foot of the seat. So that in the final

analysis, since there is no lap-component to this system, the lower body is free to swing violently forward with a torqueing motion. The passenger thus literally "hangs" himself!

Impingement of the diagonal seat belt causes fracture of every rib on that side, rupture of the spleen with massive intra-abdominal haemorrhage. The belt traces a visible outline of ecchymosis from the right (or left) shoulder to the left (or right) thigh. The diagonal belt alone cannot prevent both the head and the knees from impacting the panel; these diagonal belts do not prevent injuries to the head and chest – infact they actually cause these injuries.

Consequently, injuries with diagonal belts only, are usually instantly fatal and mainly caused by high proportion of rib fractures and thoracic injuries from impingement upon the diagonal belt.
If the diagonal belt is worn properly, like diagonal over left shoulder as in driver position, possible injuries could be:
Complete avulsion of the pectoral muscles, severe intra muscular haemorrhages; communited fracture of all the ribs from 2-6 on the left side; entire chest wall could present massive destruction with extensive haemorrhage of the inter coastal muscles, echymotic haemorrhage of the pericardium, laceration of apical lobe of the lung, anterior mediastinal haemorrhage, haemorrhage of hilum of the liver, ; extensive bruise of the axilla, , pericapsular haemorrhage of the adrenal gland, splenic haemorrhage, rupture of the sigmoid colon etc.[29]

Other injuries from diagonal belts include multiple fractures of the ribs, ruptured spleen, fractured clavicles, oblique fracture of the sternum, ruptured liver, rupture of left atrium.
Even looseness of the belt permits several inches of forward movement of the thorax – even though it prevents contacts with the steering assembly
Loose incorrectly placed lap-belts do not produce the extent of trauma observed in the single diagonal belt restraint impacts.

Combination of Lap-belt and Diagonal Belt.
A combination of lap belt and diagonal belt produces a three-point restraint system called Type II systems.
These three point restraint systems (Type II) systems produce comparatively minor injuries – including external belt contusions. This system thus offers much better protection than the diagonal or lap-belt systems alone.
However, injuries common with this system include neck injuries – consisting of intra-muscular haemorrhages extending from the 1st to the 6th cervical areas of the neck, extensive areas of sub-pleural haemorrhage along with large contusions of the shoulder due to the belt. There can also be a total dislocation of the occipital atlantoid joint. These are caused by impingement of the neck upon the belt and this can lead to instant death.

The "Submarining" Effect
Occasionally, a passenger may be wearing a properly anchored shoulder harness but the lap belt is loose. During deceleration, such an occupant, especially children, will slide (submarine) under the loose lap belt so that the seat belt now acts like a lap belt with the axis of rotation near the umbilicus.[30]

The Double Parallel Shoulder Harness
It has been shown that the double (parallel shoulder) harness provides the best restraint function than other types – including the three point belt system:

- It allows for the distribution of the applied loads to the two belts and this is greater and better than the same loads applied to a single belt. Therefore there is less belt stretch resulting in a greater restriction of forward movement.
- During an accident/impact, there are various combinations of omnidirectional forces that have a tendency to cause a body-torquing action which will be more in a single diagonal (three point) restraint resulting in less efficient restrain function.
- LOWER BELT ANCHORAGE. In a typical three-point system (Type II), the relative positions of the seat-belt tie-down which ultimately establishes the seat-belt angle is important: too forward a tie-down, can compromise the efficiency of a restraint system. Hence the need to balance a tie-down system.
- UPPER BELT ANCHORAGE. Similarly, in the three-point restraint system, the location of the upper belt anchorage also influences the efficacy of the system. If the upper anchorage is too far forward, (relative to the seated occupant)

the belt angle will be too low on the shoulder, the individual cannot only flex over it and slip out but will also be torqued forwards and sidewards during deceleration – which is particularly injurious.

- Conversely, if the anchorage is too far to the rear relative to the seated occupant, the diagonal belt will impinge upon the neck causing discomfort – even during normal driving. This creates pressure upon the blood vessels of the neck – particularly, the carotid artery, the nerves etc with a subtle disastrous effect. So that in an impact or rapid deceleration, severe neck injuries occur.

Double shoulder harnesses.

Double shoulder harnesses do not produce such grave injuries.

Except in racing cars, no seat belt injuries to automobile occupants have been reported with the double shoulder harness system [31-33] It provides more restraint to the upper torso resulting in fewer head and neck injuries – including the bruising caused by the seat-belt assembly!

CONCLUSIONS.

- Seat belts in general, greatly assist automotive occupants to prevent more extensive or fatal injuries compared to unbelted occupants.
- Their greatest usefulness is in roll-over type of accidents and in preventing ejection from the vehicle.
- Thus the major usefulness of any seat belt restraint system is the prevention of ejection during impact. [34-36]
- The relative risk taken by an occupant without a seat-belt is 70% higher than that for a belted occupant.
- While some seat belt restraint systems offer greater protection than others, even the best system can offer poor protection under some circumstances.
- The shoulder belt produces a more serious injury – (chest and leg injuries) than the Lap belt.
- The users of Lap belt only, are more prone to head injury.
- Consequently, "The shoulder strap is not to be used without a lap belt"!
- The full body restraint system provides good protection in the most severe of accidents compared to other types of restraints.
- Seat-Belt injuries are more common in front-seat passengers and in frontal impacts (head-on collisions).

Therefore:

To provide seat-belts is not enough. People must wear them and wear them correctly. Analyses of biomechanical mechanisms of trauma show that of all the four restraint systems, the double harness system offers the best protection, while the single (diagonal) system is the most dangerous.

So the seat – belt, properly installed, and properly worn, offers the best protection for the automotive occupant during impact.

To wear a seatbelt properly, it must be born in mind that while attachment or anchorage (also called "tie-down") of the restraints systems are biomedical automotive engineering techniques this anchorage is usually to the floor on both sides of the seat at a belt-angle of $40\text{-}60^0$ to the horizontal.

For Lap belts, attachment (anchorage or tie-down) is to the floor of both sides of the seat.

For the diagonal (or bandolier) belt anchorage is to the B-post pillar or above the rear door and should stretch across the shoulder and chest on the outboard side and get anchored to the floor.

Thus, when properly worn, the diagonal belt should extend across the shoulder joint and chest on the outboard side, across the flank to the opposite side where it is anchored to the floor. This provides diagonal vertical support from the hip on the one side across to the contralateral shoulder.

Meanwhile, the lap portion of the belt should lie horizontally across the anterior aspect of the heavy pelvic bones (the anterior superior iliac spines), across other pelvic structures and pelvic areas and never above the umbilicus – no matter the shape of the abdomen even in pregnancy!

While the diagonal belt provides support to the torso – from the hip on the one side to the contralateral shoulder joint it must never be used without a lap belt component!

Lap belts alone reduce 20-35% of injuries while diagonal belts reduce 65-80% of the injuries

This three point restraint systems (referred to as Type II systems) produces comparatively minor injuries – including external belt contusions and offers much better protection than the diagonal or lap-belt systems alone.

It is a full body restraint system and provides the

best protection even in the most severe of accidents compared to other types of restraints.

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