

SPINE FRACTURES

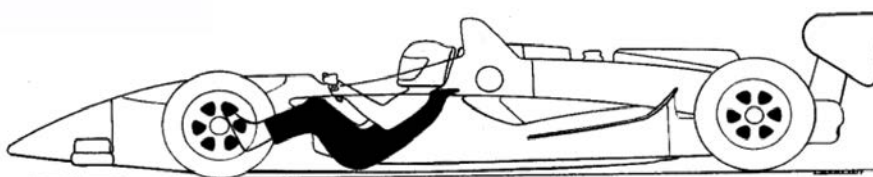
IN DRIVERS OF OPEN-WHEEL OPEN COCKPIT RACE CARS

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This paper is intended to explain the mechanisms responsible for production of spinal fracture in the driver of an open cockpit single seat, open-wheel racing car (Indy Car) and what can be done to lessen the risk of fracture.

In a report of fractures in multiple racing series drivers (Championship Auto Racing Cars [CART]/Champ cars, Toyota Atlantics, Indy Racing League [IRL], Indy Lights and Formula 1 [F1]), full details of the crash and mechanism of injury were captured and analysed. This author was the treating physician in all cases from 1996 to 2011. All images, medical records, data available from the Accident Data Recorder-2 (ADR), crash video, specific on track information, post-accident investigation of damage and direction of major impact correlated with ADR-2 data were analysed. Results provided groundwork for understanding spine fracture and forces applied to the driver in an open-wheel open cockpit race car¹.

The Indy Car requires drivers to be seated in a position such that the spine is out of its normal contour. Spinal injuries typically occur in impacts directed rearward (most common), frontward or vertically (the impact occurs on the bottom of the car after being airborne). Basilar skull fractures are the most feared due to high incidence of mortality. They occur in all forms of racing and were the first to be addressed.



- Seated angle (approximately 45°)
- Hips and knees flexed
- Lumbar spine flexed
- Seated semi-reclining

Figure 1: Body alignment in the Indy Car.

BASILAR SKULL FRACTURE

Following a fatal distractive basilar skull fracture in 1999, the Head and Neck Support (HANS) device was introduced into Indy Cars. Basilar skull fracture occurs when neck tension exceeds 3113.75 N forces.

No data demonstrates that HANS predisposes the wearer to other cervical fracture. In a high G frontal impact, the HANS yoke will cause bruising of the upper back and posterior aspects of the shoulders and tenderness of the prominence of the C7 spinous process (known as 'HANS tattoo' among racing physicians). These devices are now referred to as Frontal Head Restraints (FHR). Their primary design couples the head to the torso with resulting reduction in distractive forces on the upper neck/skull junction.

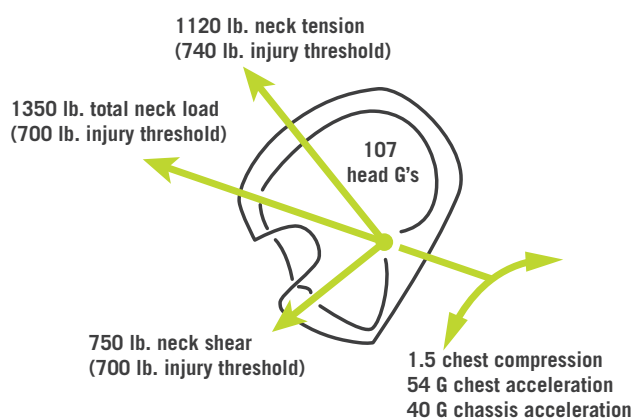
Use of this specific safety feature is compulsory in most professional motorsport sanctions and has resulted in a dramatic reduction to near elimination of fatal basilar skull fractures. No basilar skull fractures have occurred in the IRL since the introduction of the HANS and since 2006 there has been only one cervical fracture.

FRACTURES OF THE CERVICAL SPINE

Some common perceptions exist regarding the cause of fracture in the subaxial cervical spine. One is that head impact loads the cervical spine in compression (similar to a diving accident where the head impacts the bottom of the pool). In a car, this is the same as the head impacting the vehicle roof. Secondly there are injurious motions or extremes

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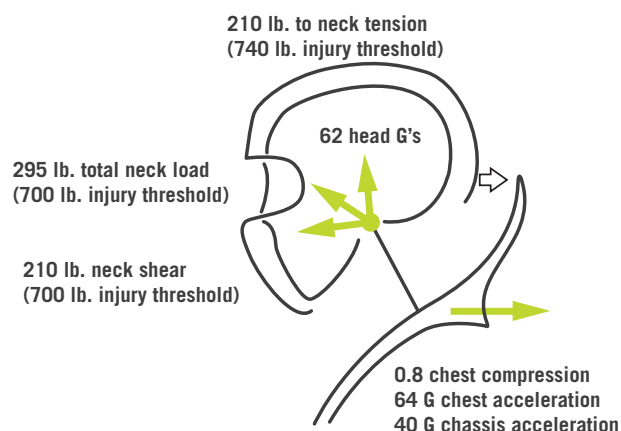
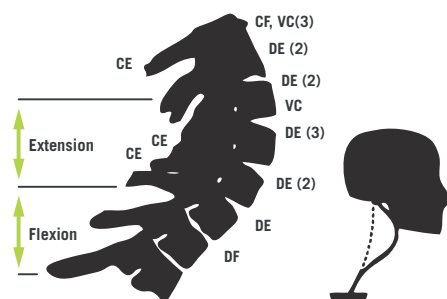


Figure 2: HANS diagrams.
HANS=Head and Neck Support.

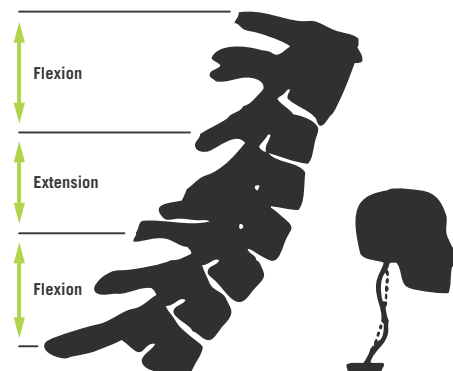
Figure 3: First order buckling of the cervical spine.

Figure 4: Second order buckling, resulting in both extension injury and flexion injury simultaneously.

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of flexion and extension. Unlike injuries seen in the general public², this is seldom seen in race drivers – signs of head impact are usually absent and significant head injury associated with cervical fracture is uncommon. Head and neck motion (flexion versus extension) has no association with the mechanism of injury³.

However, constraint to head motion increases the likelihood of neck injury. This occurs because the head is a constraint due to its mass and, as such, increases neck loads. Preflexion of the cervical spine appears to alter the types of injuries produced, yielding a greater incidence of lower cervical compression and burst fractures than a neutrally positioned spine. It increases the flexural rigidity of the spine, thereby decreasing its propensity to buckle.

The resulting neck fails as a column and injuries due to bending moments (posterior element fractures, soft tissue injuries and facet fractures) are less common.

Data derived from human and cadaveric testing and use of Anthropometric Test Dummies (ATD) has helped determine timing of head and neck motion during an injury scenario. When appropriate load is applied, neck injury occurs within 2 to 20 milliseconds, muscle contraction from 50 to 65 milliseconds, while head motion actually occurs from 90 to 130 milliseconds. Even if the event is anticipated it is not possible to contract the neck muscles before the event that results in fracture is over, and head motion does not occur until after the event is over. This supports evidence that the head acts as a constraint by virtue of its

mass, causing increased loads on the neck. Further, it shows that head motion does not contribute to cervical fracture.

Cervical fracture occurring in the absence of head impact is due to constraint of the head which, depending on the position of the cervical spine, results in first or second order buckling. Buckling is a term used to describe mechanical instability in which a structure deforming primarily in compression suddenly changes its deformation to a pattern of primary bending with compression². This produces the extremes of motion and resultant loading within the cervical spine. Second order buckling provides an explanation for seeing an injury in flexion in one region of the cervical spine and an extension injury in another.

WHAT CAN WE LEARN FROM THIS?

- Remove or neutralise anything that increases the head constraint.
- Reducing the head restraint by use of a head surround.
 - Provide adequate energy absorption.
 - Made with resilience and stiffness without cavitating or ‘grabbing’ the head.
 - The head is an inertial constraint.
 - Torso accelerates toward the head.
 - Mass of the head experiences acceleration lag (cannot get out of the way).
 - Results in increased loading on the neck.
- Head comfort pads should not be used.
 - Passenger cars and other types of sedan comfort pad should be hard and slick to reduce frictional constraint between it and the head so as not to cavitate.
- The FHR should transition between the seatback and the head surround.
 - A ‘tall HANS’ lessens the likelihood that it will dig into the head surround thus reducing the constraint of the head and resultant neck loading.

An unintended benefit of the combination of head surround, tall HANS and tuning of the head surround to prevent cavitation has resulted in a reduced incidence of cervical fractures from 23.7% of spinal fractures to 6.7%.

FRACTURES OF THE THORACIC, THORACOLUMBAR, LUMBAR AND SACRAL SPINE

When fractures of the thoracic, thoracolumbar and lumbosacral spine were analysed and stratified based on direction of the major impact vector, the majority resulted from rearward impacts. Each was classified according to Gertzbein’s Comprehensive Classification System⁴. All of the thoracic, thoracolumbar and lumbar fractures resulting from a rearward directed impact were classified as Type A fractures, most in Group 2 and in subgroups 1, 2 or 3. These have in common that the major injury vector is a compressive force on the vertebral body.

	FORWARD (N)	REARWARD (N)	AXIAL (VERTICAL) (N)
Thoracic	2	7	3
Thoracolumbar	4	8	0
Lumbosacral	0	3	1

Table 1: Direction of impact and region of spinal fracture (1996 to 2005).

SEVERITY OF INJURY SCALE	
Criteria	Description
1 Compression fracture without deformity	Not initially present on plain X-ray and often not appreciated on CT. Evident on MRI T2 sequence and/or STIR sequence. Oedema and haemorrhage into the vertebral body adjacent to the endplate. This fracture may settle until it meets Type 2 criteria
2 Mild compression fracture	<10% compression (single endplate); <15° wedging
3 Moderate compression fracture	>10% but <30% compression; >15° but <30° angulation
4 Severe compression or burst fracture involving a single endplate	≥30% compression; ≥30° wedging
5	Type 4+ injury to the posterior ligamentous complex (PLC)
6	Fracture dislocation; burst fracture involving both endplate; cord or other spinal neurological injury.

Table 2: Severity of Injury Scale. CT=computed tomography, MRI=magnetic resonance imaging, STIR=short TI inversion recovery, PLC=Posterior Ligamentous Complex.

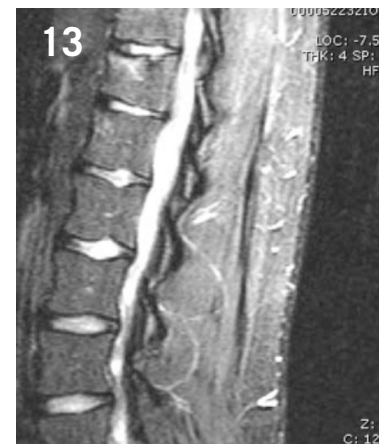
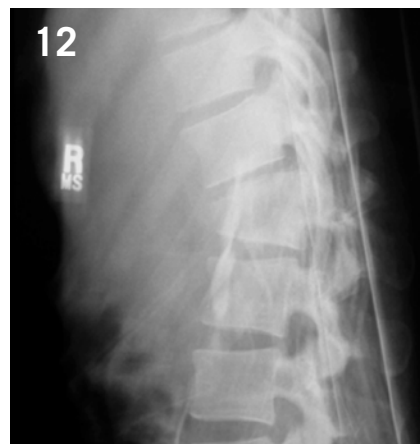
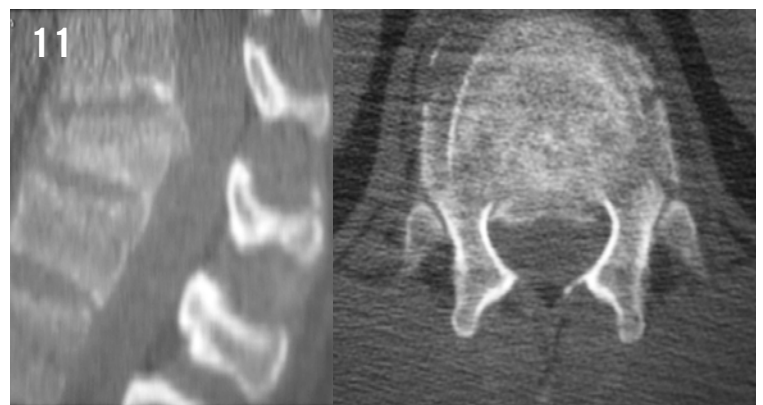
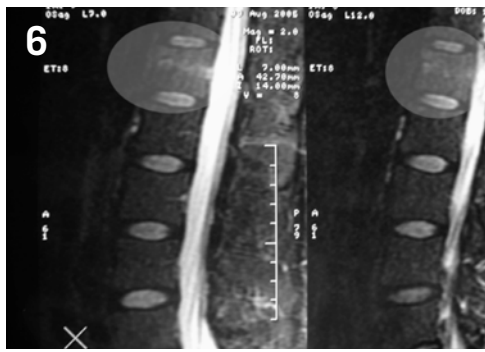
In order to quantitate the severity of fractures we created a Severity of Injury Scale (Table 2). Analysis revealed that fractures occurring in a rearward directed crash were more common (2 out of 3) than those occurring in a frontal crash. However, fractures occurring from a frontal impact were more severe (4.5 to 5) than those from rearward (2.4 to 3.3).

STUDYING THE MECHANISM OF INJURY

We examined occupant kinematics and its effect on production of injury utilising a multipronged investigation. The position of the driver’s torso and neck as well as hips and knees was investigated. A driver was positioned in his seat in an actual race

car chassis modified to allow full-length spinal X-rays. X-rays of the spine were obtained and segmental angulation was measured as well as global lordosis and kyphosis. Individual drivers’ seats were scanned to determine the frequency of and variations in angulation and alignment of the seatback. This showed that the average inclination of the thoracolumbar and lumbar spine was 45±5°. Individual drivers were also measured to obtain anthropometric data. This helped identify the average driver (1.72 m, 70 kg).

Using a Hybrid III ATD and fully loaded Indy Car, a rearward directed crash was conducted, recording loads applied to the dummy and capturing the event with high



speed videography. Following impact, the car lifted off the surface to an angle of about 45°. The ATD rose upward out of the seat with spinal extension of the thoracic spine. Seat back angle (45°) plus elevation of the car resulted in the 'driver's' thoracolumbar spine being almost horizontal during the crash pulse. This helped to explain how a horizontally directed crash pulse could result in an axial load on the spine causing a compressive fracture (horizontally directed force applied vertically to seated driver). This axially applied load is also the result of the vector sums of the rearward and vertical components of the impact. The resultant of these two vectors can explain the variation in location of injury within the spine.

Figure 6: Type 1: vertebral body contusion without deformity. Only present on MRI. Best seen on T2 and STIR sequences. MRI=magnetic resonance imaging, STIR=short TI inversion recovery.

Figure 7: Type 2: vertebral body compression of <10% and vertebral wedging of <15°.

Figure 8: Type 3: >10% and <30% vertebral body compression; >15° and <30° of vertebral body wedging.

Figure 9: Type 4: ≥30% compression and ≥30° vertebral wedging ± PLC injury. PLC=Posterior Ligamentous Complex.

Figure 10: Type 4: sagittal image of fracture.

Figure 11: Type 5: burst fracture.

Figure 12: Type 6: fracture dislocation.

Figure 13: MRI T2 image of fracture resulting from vertical impact. MRI=magnetic resonance imaging.

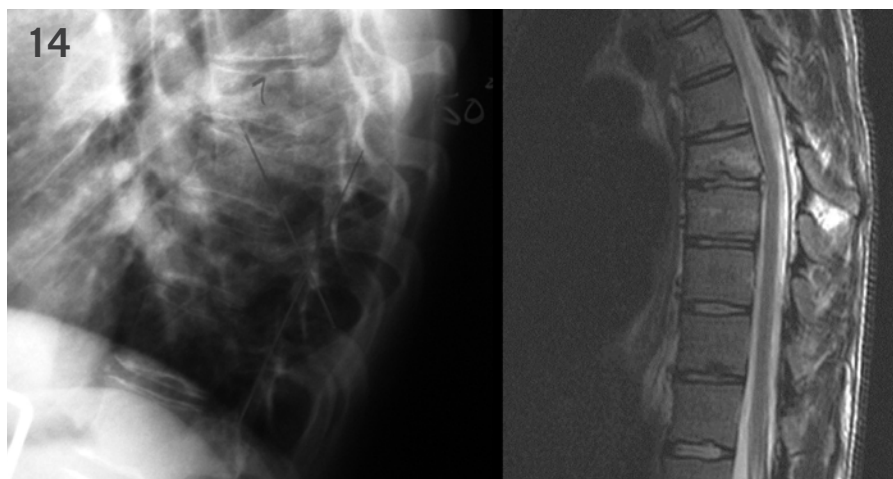


Figure 14: Spinal fracture sustained by driver in a rearward impact. This allowed researchers to use human field data with their model.

Fortunately for the research team, the driver who participated in the X-ray analysis was involved in a rearward directed crash and sustained a spinal fracture providing the needed field human data from a driver that had been X-rayed and measured in his racing car prior to injury, crashed in a rearward directed manner, in a car that was instrumented with an ADR-2 and sustained a spinal fracture. This provided data needed to proceed with computer modelling, resulting in validation of injury thresholds needed to develop systems designed to protect the driver from spinal fracture in a rearward crash.

THE RESULTS

We now have an appreciation for the human tolerance for spinal injury. The spine can only tolerate $60\text{ g} \leq 3\text{ ms}^5$ – this load applied for $>3\text{ ms}$ will result in injury. In the lumbar spine we can break it down to tension and compression loads. In tension, the spine can only endure $\leq 3860\text{ N}$ and in compression $\leq 7140\text{ N}^6$. Anything larger will result in fracture. Compressive load tolerance was studied based on the area of the spine. From T7 to T12 a load of $3264 \pm 1211\text{ N}$ ($\geq 4475\text{ N}$) and from L1 to L5, $4590 \pm 2061\text{ N}$ ($\geq 6651\text{ N}$)⁷ can be tolerated. This data was derived from cadaver testing and math modelling. Being based on an assortment of specimens (various ages and states of health), it is presumed that a young healthy muscularly fit driver will have a somewhat higher threshold for injury. The IRL uses 6500 N as threshold for spinal fracture. An axially applied load along the spine of $>20\text{ g}$ is the threshold for compressive failure (fracture) of a vertebra.

Through analysis of data the sequences of kinematics occurring in a rearward crash were determined:

- Thoracolumbar spine is in a kyphotic position with the thoracic spine in a forward flexed posture.
- Pelvis is fixed with the lap belt and crotch straps.
- Car rotates into a rearward leading position as the driver's torso is pulled out of the seat back and the thoracic spine is further forward flexed.
- Car strikes the barrier and driver's torso is accelerated back into the seat, impacting seat with the apex of the thoracic kyphosis.
 - Dorsal to ventral force is applied resulting in a compressive load to the vertebra adjacent to the apical vertebra*.

*We term this the 'Viano effect' – a compressive load on the thoracic vertebra. When the torso ramps up the seat back (due to inability of the seat and safety harness to prevent motion of the torso and pelvis along the seat back), inertial loading is added to the compressive loading (the Viano effect). Upward rise of the shoulders is stopped by the safety harness and additional compressive loading occurs⁸.

This results in sufficient compressive load to fracture. Depending on the size of the driver and the degree of compression the torso is rolled into forward flexion under the shoulder belts, increasing the degree of flexion in the thoracic and thoracolumbar spine. This adds a distractive component that has the potential to cause injury to the Posterior Ligamentous Complex (PLC).

PREVENTIVE MEASURES

Seating position

The backward tilted seated posture is a result of the need to sit as low in the open cockpit car as possible. This prevents the driver from sitting up out of the cockpit. This posture is unique to this type of racing car. In series where the driver sits more upright (e.g. Nascar), spine fractures occur with reportedly less frequency. Unfortunately, although computer modelling has established that if the driver is able to sit up so that the seat back tilt is 30° or less from the vertical, the compressive loads are reduced to sub-threshold for the average rearward crash pulse. This is not a viable option in this formula.

Coupling driver pelvis and torso to seat

This can be accomplished by creating a pelvic 'bucket' that fits to the pelvis and adding a prominence that promotes normal lumbar lordosis. These factors combine to reduce the compressive loads on the thoracic and thoracolumbar vertebra and the fracture risk is mitigated. The pelvic bucket is most easily accomplished in a driver with a broader pelvis and gluteal contour (norm in female drivers). The seat material designs should cavitate and allow the pelvis to 'sink in' to the seatback like a baseball into a catcher's mitt but not 'bottom out' (what happens when you catch a baseball and it stings your hand through the glove). Promoting normal lumbar lordosis has the effect of retaining the pelvis in the seat, thus lessening the ramping effect (the rearward crash kinematics) as well as the out-of-position excursion that occurs when the vehicle swaps ends. The result is a settling of the pelvis and lower torso into the seat, reducing the Viano effect and ramping phenomena.

Seat modifications developed from this research have resulted in a reduction in the occurrence of fracture in rearward impacts. In the interval 1996 to 2005 rearward impacts accounted for 65.7% of the spinal fractures. From 2005 to 2011 this has been reduced to only 20%. No spinal fractures



Since the introduction of this chassis in 2012, no resultant fractures have occurred.

resulting from a rearward directed impact have occurred since 2007 (when the current seating platform was introduced and fully integrated with the flush head surround and tall HANS). It also correlates with the uniform presence of the SAFER (Steele and Foam Energy Reduction) barrier at all IRL oval tracks.

SPINAL FRACTURES OCCURRING FROM VERTICAL IMPACT (Z AXIS LOADING)

A distinct subgroup of fractures occurred with forces applied directly to the bottom of the car. Impacts generating these forces were usually the result of the car being launched and falling from a height. ADR-2 recordings in these cases were always >20 g in the z axis.

Investigation included the construction of a buck that allowed for impact onto the bottom. Foam was used to fabricate the seat bottom and multiple thicknesses were tested. The results showed it was necessary to use 76.2 mm of a specialised foam padding in order to reduce the compressive loads recorded at the T8 and T12 load cells to <6500 N. However 38.1 mm of the foam reduced the loads to around 8000 N9.

PREVENTATIVE MEASURE

The IRL DW12 Chassis has a foam insert 30 mm thick in the chassis bottom to help lessen the risk of this injury. Since the introduction of this chassis in 2012, no resultant fractures have occurred.

SPINAL FRACTURES RESULTING FROM FRONTAL IMPACTS

From 1996 to 2005, spinal fractures occurring from frontal impacts accounted for 18.4% of total and had a greater severity index. From 2006 to 2011 they increased to 40%. This was thought to be due to preventative measures previously described, which lessened the risk of spinal fracture in a rearward impact.

A study of driver kinematics in frontal impact has been initiated, the first phase of which was a doctoral thesis by Ms. Tara Troxel¹⁰. Using data supplied from the IRL archives she was able to study five frontal crashes that resulted in spinal injury.

TROXEL METHODOLOGY

Analysis consisted of fractures where load, load path and result were known. Using adaptation of a finite element model Troxel predicted fractures with the known data and analysed parameters that could be altered to identify risk factors and their role. She concluded that use of Hybrid III ATD over-estimates spinal loads, there were high moments in flexion (highest at T10 and lowest at L1), but moments did not correlate with level or severity of injury. Instead, the upright posturing of the driver was most significant as it maintained anatomical curvature of the spine in the sagittal plane while the load transfer utilised physiologic spinal curves which act as a dampened spring. She determined the optimal seating posture to be reclined 25° from the vertical with shoulder belts 75 mm above horizontal and including a thigh 'hump'.

KINEMATICS

In order to better understand the kinematics of the driver influenced by a restraint system in a frontal impact, a series of simulated frontal impacts were completed with variations of shoulder harness/lap belt/crotch straps tested.

The testing demonstrated the following in frontal collision: the pelvis slides forwards under the lap belt, antisubmarine (crotch) straps stop the forward excursion of the pelvis and the torso rotates forward around the pelvis. This results in a compressive loading of the vertebra and, if the rotational moment is great enough, can result in distractive forces on the posterior column of the spine (PLC).

PREVENTATIVE MEASURES

To date we are not able to offer any recommendations to mitigate the risk of spinal fracture in an Indy Car, single seater, open-wheel racing car. The most correlative finding in Troxel's work (validated by previous sled testing) is the torso position. She concluded it would be necessary for the torso to recline no more than 25° from vertical. This is not an option in the current version of an Indy Car where the seated posture remains about 45° from vertical. However there is an investigation underway which would place a compressible panel under the pelvis and thighs to allow the pelvis to settle forward rather than sliding forward.

SUMMARY

- Spinal fractures are seen with increasing frequency in drivers of Indy Cars.
- Distractive basilar skull fractures have largely been eliminated with the use of a FHR.
- Cervical fractures are much less common since the introduction of the HANS coupled with an improved cockpit environment (head surround and head surround seat junction and the elimination of comfort head pads) and use of the extended (tall) HANS.

- Spinal fractures are seen in three distinct types of impacts:

1. Rearward – most frequent less severe.
2. Frontal – less frequent more severe.
3. Vertical – when the car lands on its bottom after becoming airborne.

- Risk of fracture in a rearward impact is lessened by proper seat contouring and selection of seat foam material and proper transition from seat back to head pad.
- Head pad should minimise frictional loading between extended HANS and head surround.
 - Head pad should provide sufficient energy management to lessen risk of head injury but should not cavitate.
- Risk of spine fractures that occur from vertical impacts are lessened by adequate foam padding in the seat bottom.
- Spinal fractures that result from frontal impacts are being investigated but to date no solution specific to this formula has been found.
- The seated posture in this formula seems to predispose to spinal fracture as research has indicated that a more upright posture is less likely to result in fracture.

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