

Analysis of Driver Kinematics and Lower Thoracic Spine Injury in World Endurance Championship Race Cars during Frontal Impacts

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ABSTRACT

This study used finite element (FE) simulations to analyze the injury mechanisms of driver spine fracture during frontal crashes in the World Endurance Championship (WEC) series and possible countermeasures are suggested to help reduce spine fracture risk. This FE model incorporated the Total Human Model for Safety (THUMS) scaled to a driver, a model of the detailed racecar cockpit and a model of the seat/restraint systems. A frontal impact deceleration pulse was applied to the cockpit model. In the simulation, the driver chest moved forward under the shoulder belt and the pelvis was restrained by the crotch belt and the leg hump. The simulation predicted spine fracture at T11 and T12. It was found that a combination of axial compression force and bending moment at the spine caused the fractures. The axial compression force and bending moment were generated by the shoulder belt down force as the driver's chest moved forward. The axial compression force at the spine was also induced by the forces from the crotch belt and the leg hump. Based on these mechanisms, the modifications were made to help reduce the spine fracture risk. The seat back angle was raised, the shoulder belt anchor was lifted, the crotch belt anchor was moved forward, the seat pad thickness was increased and the seat pad stiffness was reduced. These modifications allowed more forward motion of the pelvis and reduced the shoulder belt down force, and generated no spine fracture.

CITATION: Katsuhara, T., Takahira, Y., Hayashi, S., Kitagawa, Y. et al., "Analysis of Driver Kinematics and Lower Thoracic Spine Injury in World Endurance Championship Race Cars during Frontal Impacts," *SAE Int. J. Trans. Safety* 5(1):2017, doi:10.4271/2017-01-1432.

INTRODUCTION

According to the NSCISC (National Spinal Cord Injury Statistical Center), there are approximately 6,500 of the spinal injuries caused by car crashes in the United States [1]. Melvin, J. et al. [2] reported the low injury potential for the head, neck and torso in Indy Car racing while a high injury risk for the thoracolumbar spine is indicated [3, 4, 7]. Trammell, T. et al. [3] reported that 40 spine fracture incidents had occurred in Indy Car racing between 1996 and 2006, and the authors indicated that the spine region between 11th thoracic vertebra and 2nd lumbar vertebra tended to be the predominant fracture location. Pintar, F. et al. [5] investigated the motor vehicle accidents in the United States and reported that spine fractures also tended to occur in frontal crashes more than in other crash types. The spine fracture in motorsports has been studied by researchers Trammell, T. et al. [6] and Amenson, T. et al. [7]. Trammell, T. et al. analyzed the mechanism of a spine fracture in rear impact of Indy Car using MADYMO and investigated the relationship between the driver kinematics and the spine stress.

Amenson, T. et al. analyzed the influence of seat back angle, the shoulder belt anchor location, the leg hump and the spine curvature in Indy Car using the MADYMO Race Car Driver Model (RCDM) to predict thoracolumbar spine injuries during frontal impact.

The objective of this study was to identify the injury mechanisms of race car driver spine fractures during frontal impacts in the World Endurance Championship (WEC) series, and to investigate possible modifications of the seat/restraint systems to help reduce the spine fracture risk. Finite element (FE) simulations were used to understand the spinal fracture mechanisms, the driver kinematics and interactions between the driver and the seat/restraint system. The Total Human Model for Safety (THUMS) was scaled to the driver size and incorporated with a model of the detailed racecar cockpit and a model of the seat/restraint systems. THUMS Version 4 was jointly developed by Toyota Central R&D Labs, Inc. and Toyota Motor Corporation [8]. To identify spine fracture mechanisms and to investigate the influence of driver anthropometry on injury outcomes, a small driver and a large driver were modeled in the frontal impact crash simulations. Additional simulations changing the parameters of the seat/restraint systems were conducted to investigate possible modifications to help reduce the spine fracture risk. The shoulder belt angle, the seat back angle, the seat pad thickness, the shape of leg hump, the crotch belt anchor position and the seat pad stiffness were selected as the parameters. This study was conducted as cooperative research between the Federation Internationale de l'Automobile (FIA) Institute and the Toyota Motor Corporation.

METHOD

Model Development

LMP Cockpit Model

A WEC racecar was modeled based on CAD data. The monocoque structure, carbon seat, seat pad, six-point seat belt, helmet, head surround and Head and Neck Support (HANS®) were modeled. **Figure 1** shows the cockpit and driver models. The total elements of this model was approximately 2,200,000. The average element size was 5 mm. The positive X direction was defined as forward, the positive Y direction was defined as being to the right looking forwards in the car and the positive Z direction was defined as downward.

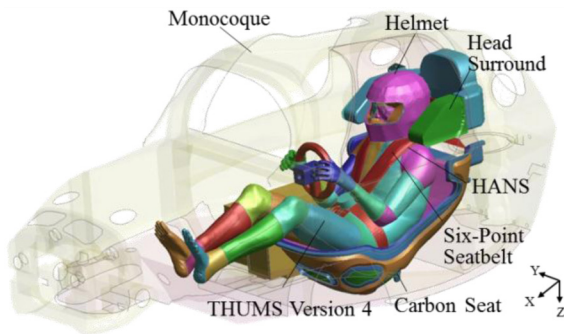


Figure 1. Cockpit and driver models

Driver Model

The THUMS Version 4 AM50 Occupant model has been validated by comparing the mechanical response and the injuries between the literature and the dynamic simulation [7]. **Figure 2** shows the driver models of two anthropometries. The left figure shows Driver A (160 cm height, 55 kg weight) and the right figure shows Driver B (185 cm height, 80 kg weight). The THUMS Version 4 AM50 (177 cm height, 74 kg weight) was scaled by the ratio of driver height between the original THUMS (176 cm height) and the target drivers.

The spine postures of the driver models were derived from Magnetic Resonance Imaging (MRI) images of the real drivers seated in a WEC seat. The MRI images were supplied by the FIA Institute.

In the WEC series, three drivers share driving duties and rotate throughout the race. Each driver has a different anthropometry that the seat and restraint system must accommodate to keep the driver safe. The two driver models used in this study represent the smallest and the largest drivers of one team and the influence of anthropometry was investigated in frontal impact simulations using both models. Driver A represents the small driver. Driver B represents the large driver. **Table 1** summarizes the anthropometry of the THUMS model, Driver A and Driver B.

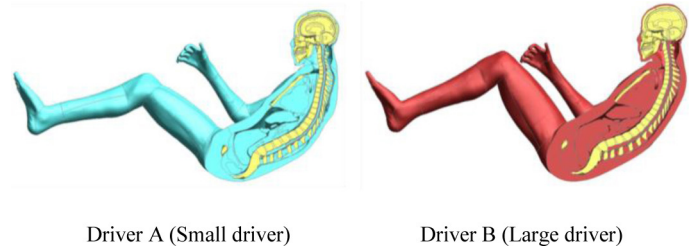


Figure 2. Driver models.

Table 1. Height and weight of THUMS, Drivers A and B.

Injury	THUMS Version 4 AM50	Driver A	Driver B
Height [cm]	177	160	185
Weight [kg]	74	55	80

Seat and Six-Point Seat Belt Model

Figure 3 shows the models of the carbon seat, the seat pad and the six-point seat belt. The belt restraint system consists of two shoulder belts, two lap belts, two crotch belts and a buckle. One belt end connects directly to the monocoque seat while the other belt end connects to the buckle.

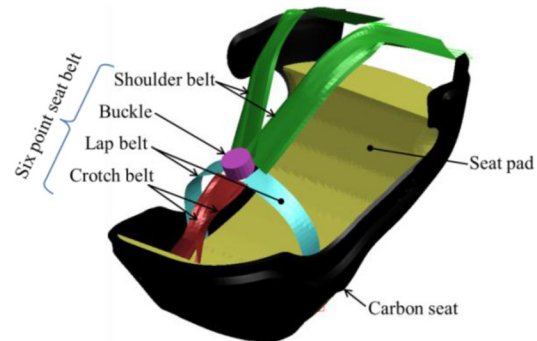


Figure 3. Models of carbon seat, seat pad and six-point seat belt.

Input Pulse

The SFI crash pulse (SFI specification 38.1) is used for the simulation in this study. It represents a severe frontal impact. The direction of the pulse is only in the X direction. The peak value is 70 G (**Figure 4**).

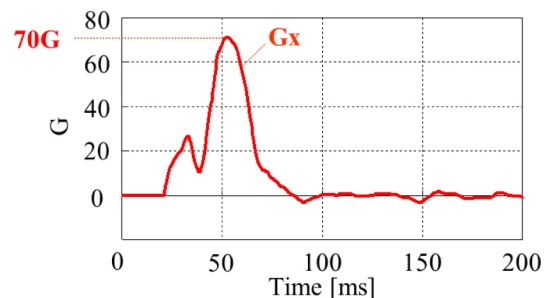


Figure 4. SFI 38.1 crash pulse.

Index of Spine Load

Axial Compression Force and Bending Moment

This study estimated the axial compression force (F) and the bending moment (M) in the cross section of the vertebra to investigate the stress on the spine. [Figure 5](#) shows a lateral view of the spinal curvature of a seated race car driver. Each cross section passes through the vertical center of each vertebra, level with the upper face of each vertebra. [Table 2](#) shows the cross-sectional area A and the section modulus Z in the cortical bone of each vertebra. Both the axial compression force component F and the bending moment component M of the spine stresses were calculated per [equations \(1\)](#) and [\(2\)](#). The spine stress z of each vertebra is calculated as the sum of σ_F and M according to the [equation \(3\)](#).

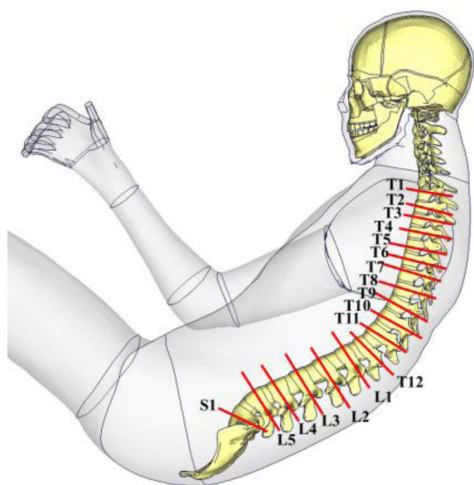


Figure 5. A lateral view of the spinal curvature of a seated race car driver.

Table 2. Cross section area and section modulus in both Driver A and B.

Driver	Driver A (160 cm height)		Driver B (185 cm height)	
	A [mm ²]	Z [mm ³]	A [mm ²]	Z [mm ³]
T1	176	1520	206	2040
T2	190	1972	210	2570
T3	187	2050	220	2751
T4	194	2106	220	2725
T5	194	2157	233	2865
T6	192	2201	218	2876
T7	199	2325	224	2990
T8	204	2495	231	3181
T9	211	2534	225	3118
T10	207	2829	233	3607
T11	206	2915	232	3751
T12	193	2689	216	3365
L1	245	3089	279	3972
L2	250	3478	274	4249
L3	278	3698	304	4635
L4	328	4313	356	5290
L5	347	4765	388	6029
S1	440	5027	494	6407

$$F = \frac{F}{A} \quad (1)$$

$$M = \frac{M}{Z} \quad (2)$$

$$z = \sigma_F + M \quad (3)$$

Index and Criteria of Bone Fractures

[Table 3](#) shows the index and the criteria of the bone fractures. It was postulated that the spine fracture occurred when the plastic strain of the spine bone element exceeded 2.05 %. It was also postulated that the pelvis fracture occurred when the plastic strain of the pelvis bone element exceeded 2.35 %. The values refer to the research by Kemper, A. et al. [9]. In our study, the dynamic axial compression simulations of whole lumbar spine and the impact simulation of pelvis bone were conducted. Force-Stroke curves and fracture force in our simulation results were closed to that in references (lumbar spine: Duma, S. et al. [10], pelvis: Guillemot, H. et al. [11]).

Table 3. Index and criteria of bone fractures

Injury	Regions	Index	Criteria
Bone fractures	Spine	Plastic strain	2.05 %
	Pelvis		2.35 %

Measuring Range of Reaction Force

[Figure 6](#) shows the measuring range of the reaction forces. The shoulder belt reaction force is measured in the red range between the driver's shoulder and chest under the HANS®. The lap belt reaction force between the lap belt and the driver's abdomen is measured in the blue range where the lap belt contacts the driver's pelvis. The crotch belt reaction force is measured in the green range on the pelvis. The leg hump reaction force is measured in the orange range between the driver's pelvis and crotch.

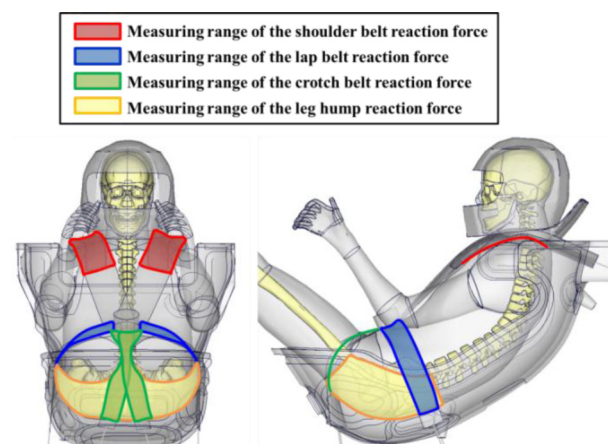


Figure 6. Measuring range of the reaction forces.

Measuring Chest Deflection

In this study, the chest deflection is measured between the sternum and the thoracic spine. Figure 7 shows the measuring point of the chest deflection. The measuring point (a) for the sternum side is the center of the sternum. The measuring point for the thoracic spine is the point between T6 and T7. The original distance between (a) and (b) is 110 mm for Driver A, 130 mm for Driver B.

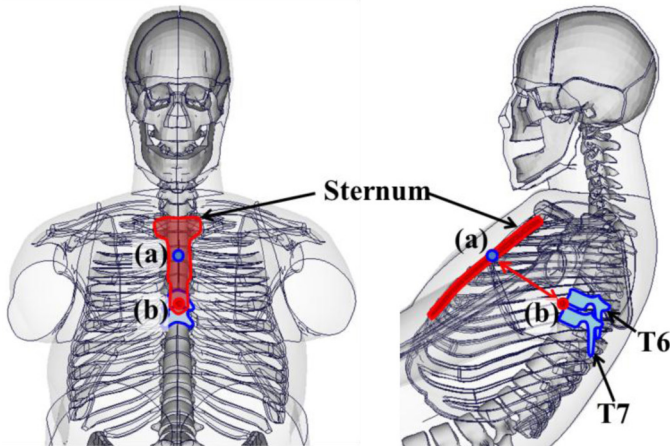


Figure 7. Measuring points for chest deflection.

Simulation Conditions

A simulation matrix comprising of ten cases with various input scenarios was run, comparing the driver kinematics, the contact forces and the bone fracture risks. The shoulder belt angle (i), seat back angle (ii), crotch belt anchor position (iii), shape of leg hump (iv), seat pad thickness (v) and seat pad stiffness (vi) were considered and changed as the parameters.

The simulations were performed using the FE code LS-DYNA™ V971. Table 4 shows the simulation conditions.

Figure 8 shows the definition of seat and restraint system, while Figure 9 shows the strain-stress curve of both the 0.3 MPa and 0.2 MPa seat pad materials.

A summary of the cases is:

- Case 1 is a simulation of the real-world impact in which Driver A was injured.
- Case 2 is Driver B in the same cockpit as Driver A in Case 1. Driver B does not use a seat pad in the car. He sits directly on the carbon seat.
- Case 3 is the case with the shoulder belt angle of Case 2 decreased from 20 degrees down to 0 degrees (horizontal).
- Case 4 is the case with the seat back angle of Case 2 increased from 35 degrees to 55 degrees.
- Case 5 is the case with the shoulder belt angle of Case 2 decreased by 20 degrees (to horizontal) and the seat pad thickness of Case 2 increased to 76.2 mm.
- Case 6 is the case with the seat back angle of Case 5 increased to 20 degrees down, and the leg hump of Case 5 flattened.
- Case 7 is the case which moved the crotch belt anchor position of Case 6 forward by 150 mm.
- Case 8 is the case which declined the leg hump of Case 6.
- Case 9 is the case which softened the seat pad stiffness of Case 8, (seat pad stiffness changed from 0.3 MPa to 0.2 MPa).
- Case 10 is the case for Driver A in which the shoulder belt angle is decreased by 20 degrees (to horizontal), the seat back angle is increased by 20 degrees (to 55 degrees from horizontal), the seat pad thickness is increased to 76.2 mm, the crotch belt anchor position is moved forward by 150 mm, and the seat pad stiffness is softened compared to Case 1.

Table 4. Simulation matrix.

Case No.	1	2	3	4	5	6	7	8	9	10
Driver	Driver A	Driver B	Driver B	Driver B	Driver B	Driver B	Driver B	Driver B	Driver B	Driver A
i) Shoulder belt angle	-20 deg	-20 deg	0 deg	-20 deg	0 deg	0 deg	0 deg	0 deg	0 deg	0 deg
ii) Seat back angle	35 deg	35 deg	35 deg	55 deg	35 deg	55 deg	55 deg	55 deg	55 deg	55 deg
iii) Crotch belt anchor position	Rearward	Rearward	Rearward	Rearward	Rearward	Rearward	Forward	Forward	Forward	Forward
iv) Shape of leg hump	Decline (40 deg)	Decline (40 deg)	Decline (40 deg)	Decline (40 deg)	Decline (40 deg)	Flat (0 deg)	Flat (0 deg)	Decline (40 deg)	Decline (40 deg)	Decline (40 deg)
v) Seat pad thickness	60 mm	None	None	None	76.2 mm	76.2 mm	76.2 mm	76.2 mm	76.2 mm	76.2 mm
vi) Seat pad stiffness	0.3 MPa	None	None	None	0.3 MPa	0.3 MPa	0.3 MPa	0.3 MPa	0.2 MPa	0.2 MPa