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Design and Fabrication of a Spine profile based anti-flexion support vest for Off-road vehicle drivers

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ABSTRACT

The present conditions of ATV's in competition oriented events like SAE-BAJA and SAE-SUPRA, as well as their increased usage in North America, demands for high performance. The straightforward and ingenious way is to reduce the overall vehicle weight by selection of stronger and lighter materials or by shortening of the roll cage which also helps in greater maneuverability. This greatly impacts the driver ergonomics of seating and egress/ingress in case of emergency. The area of interest is the repeated feedback about lower back pain from the drivers of previous year teams of SAE-Baja India as well as an increased reporting of spinal fractures and dislocation in extreme off-roading scenarios; part of which is directly related to abnormal driving postures due to packaging of driver in roll cage and repeated shocks and yaw-pitch-roll induced inertial forces on the driver during harsh driving. This research is an approach to reduce these forces or dissipate them to protect the spine from injuries and shielding the driver from driving induced back pain.

Key words: Posture, Spine, Support vest, yaw-pitch-roll

1. INTRODUCTION

Human spine as in all warm blooded animals is not a singular unit but composed of discreet bony units called vertebrae and has a hollow section between them to carry the spinal cord. The vertebrae are interlinked together and have fluid filled bladders called inter vertebral discs (IVD) and act as fibro cartilaginous joints to allow slight movement in the spine. This means that the spine is primarily focused to support the spinal cord and nervous system and acts as a central element on which the various skeletal parts are attached. The vertebral column is not designed to sustain its peak maximum loading in all orientations due to its assembly also as the IVD not being able to sustain isotropic loading. The positions at which spine is most capable of vertical (axial) loading are hence limited by the inherent structure of the spine only.

The vertebral column is capable of sustaining loads up to 10000N axially if the shoulders and hands theoretically support the weight without buckling [5], however this capacity is greatly reduced when the spine is flexed and in that case is only capable to sustain 3300N of axial loading. Similarly different loadings determine the optimum position to sit as well as to perform daily tasks without injuring the vertebral column and rupturing the IVDs.

The passenger car has resolved the seating position of the driver for long distance driving which the consumer can readily accept has "comfort "and hence cannot be neglected for ensuring product sales. Quiet surprisingly the ATV/UTV and recreational vehicle market has long ignored driver ergonomics and safety issues in case of harsh driving, instead focusing on performance and aesthetics of the vehicle. This dissonance from reality of bump/jerk induced driving means that the driver ergonomics and comfort are the last issues that are focused upon and this can be validated in competitions like SAE-BAJA where modern designs try to cramp the driver into rule constrained minimum space. This results in extreme lower back pain and potential damage, mainly due to extension and flexion of spinal column in ways it is not used to and subsequently slipped IVD's, chronic pain and in extreme cases fractures occur. According to **Thomas Jefferson University Hospital, Philadelphia, PA, USA**

"Thirty-six patients were identified from the spinal cord injury database. The male: female ratio was 11:1 of the ATV injured patient. This is statistically different from the general database population, with a males representing 70% of patients. The average ATV injured patient was 13.7 years younger than the average database patient. The incidence of an axial compression or burst type fracture morphology was significantly higher in the ATV injured patient population (50%) compared with the database population as a whole (12%). Factors predisposing patients to injury on ATVs include excessive speed, use of alcohol or controlled substances, use of machinery after dark, and inexperience."

2. PROBLEM STATEMENT

The available market solutions to the open cockpit vehicle driver support are limited to motorcycle accessories in form of stiff spinal supports made out of carbon fiber and Kevlar with nominal padding, as they primarily serve the purpose of keeping the spine straight and protect it from direct contact with hitting ground and rag-dolling, in case of accidents, as in case of helmets and elbow guards. These hence are not usable in off-road vehicles where the riding dynamics are poles apart from motorcycling. Another option is to procure contoured seats optimized according to the spinal profile. The problem here which many wearers would overlook is that seats are designed for a healthy person in his physical prime and hence are almost cocoon-shaped which presents challenges in seating and adjustment of chubbier drivers, old people and women with prominent posteriors.

Thus there was a stop-gap solution of increasing padding in normal seats in which a driver sinks during operation of vehicle and such riding sessions don't last more than a couple of hours. So comfort is overlooked, but it shows its presence in events and races when the driver utilized the vehicle for more than a couple of hours such as the endurance event in SAE-Baja when it lasts for a total of 4 hours of challenging driving in rough terrain.

3. SOLUTIONS AND DESIGN ALTERNATIVES

We devised a way by identifying the root causes of the spinal column related injuries in following scenarios:

1. Harsh riding and bump induced jounce resulting in abnormal vertebral compression in axial direction.
2. Jerks in frontal impact and rear impacts in vehicle collision with a stationary object as well as another vehicles.
3. Long term slouching in seat, most visible in hammock seats or seats with thick and soft paddings.

These were first addressed by modification of seat and dividing the seat into three parts interconnected by springs of appropriate stiffness and connected in such a way to absorb the jerk forces in a 2D plane by stretching and compressing, as well as adjusting according to static driver position, effectively mimicking a hammock but with the rigidity of a normal padded seat.

Difficulties arise when applying design for manufacturing principles; the seat became heavy when springs and associated mounts were factored alongside their strengths, the complex stitching and possible case of snapping of springs in case of misalignment or wrong seating position. This design proposal hence was abandoned in favor of a wearable vest embedded with foam filled cushions positioned to support spinal profile and absorb shocks in case of aforementioned scenarios.

1. The new vest was modeled after the riding armor and heavily modified for operation in off-roading scenarios.

2. Appropriate cushioning was done in place of seat padding and the vest is tightened on the body by the driver according to his preference thus eliminating the need of spring arrangement and mountings.

3. The vest was stitched out of stiff fire resistant material (reticulated stiff netting) providing rigidity as well as weight reduction. A rexin base was provided for isolating the driver from the backside debris and water in muddy terrain.

4. The cushion is strategically placed along the spinal curves and promote positive Lordotic and Kyphotic curves even while harshest of driving conditions and stiffer suspension setup.

4. METHODOLOGY

The basic reference for analysis of spinal column in driving conditions came from a research paper of driver injuries from tip over scenario of a forklift truck. Mechanics of the human body and spine combined can be imagined as an inverse pendulum with majority of its mass concentrated at its head and neck junction and rest gradually decreasing as we proceed down the profile [2]. The inverse pendulum, inherently unstable is stabilized by the combined action of human motion and musculoskeletal interface while in static condition. Since there is no universally agreed method and theory for analysis of spinal loading and failure under loading [4], and the Schultz and Andersen model is complex to compute for dynamic loading, we assume the axioms and data as per as the inverse pendulum model of force-moment analysis.

5. SIMULATION OF THE DRIVER:

"The potential for a fracture of the lumbar spine similar to wedge or Chance type due to a tip over can be examined using a simulation. The cause of these injuries is a rapid flexion of the operator pivoting about the lap belt restraint which is terminated by an impact with the machine or pavement. Tip over times have been measured down to 0.8 seconds for an industrial vehicle, in contrast to the times reported in real operating situations. Thus, the inertia loads on the operator for a tip over are probably not fully understood yet, at least as reported so far in the literature and takes the motion of a sit-down forklift, which is computed as an inverted pendulum, and modifies the motion of the operator H-point (hip pivot as defined by the Federal Motor Vehicle Safety Standards) at L, ϕ. The angle β of the spine measured relative to the vertical (inertial coordinates) describes the motion of the seated operator, restrained by a lap belt only."

6. ASSUMPTION OF THE DESIGN AND CALCULATIONS:

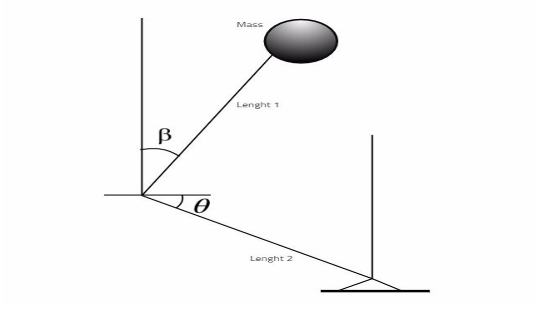

Fig 1: Inverse pendulum model of force analysis of human operator

Several assumptions are made in this model which we carried over to our modified model:

1. The human operator is suitably constrained by lap belt by his pelvic region and the spinal interface L5-S1 acts as the vertebral pivot along which articulation takes place.
2. The cervical section is restrained by muscles and operator stiffens his neck in panic.
3. Legs do not bear any loads in this seating position.
4. The fibrocartilaginous nature and damping via inter-vertebral discs is ignored so as to make the calculations linear.
5. The mass is assumed to be concentrated near the head+neck junction and the density is high enough so as to change the position of C.G. to lie somewhere near that interfaces.
6. All other data of loading limits and failures are taken from various electro-myographic data from internet and medical database from NCBI [13].

The spine column has various standardized values assigned as a threshold for failure/fracture in axial compression and attaining 75% of those peak values subject the driver/occupant to severe pain trips, increased risk of slipped disc (dislocated IVD) or disfigurement of normal spinal curvature. 6400N in axial loading/compression and 3200N in flexion is taken as limits of human vertebral column tolerance without showing any damage or chances of failure [4].

7. MODIFIED MODEL AND CALCULATIONS:

We proposed and devised a multiple inverted pendulum model to represent the human body structured around its vertebral column and ameliorated the inverted pendulum model as multiple point masses suspended on a common link rotating around a common pivot, The L5-S1 interface. The mass distribution of the body is taken as a standard used in aviation medical data-book [6] and is true to our knowledge.

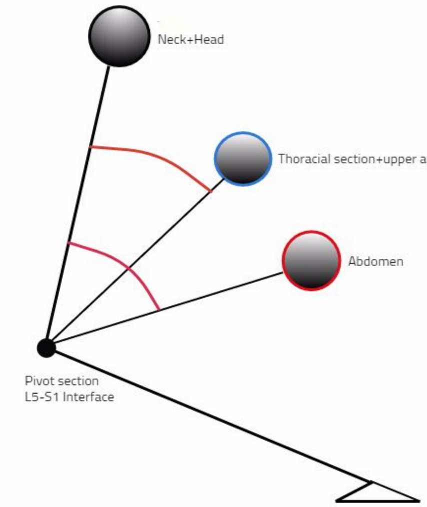

Fig 2: Modified inverse pendulum model of force analysis of human driver or operator of the vehicle

Assumptions made in superimposed multi inverted pendulum model:

1. The masses are concentrated on their C.G. at the respective distances from the fulcrum point i.e. the L5-S1 section at the lap belt restraint.
2. The body alongside the vehicle travels at 45km/h in a straight line and directly collides with an almost stationery vehicle experiencing frontal impact. The driver is restrained properly by a 5-point harness with some travel allowance in the belts due to flexing and stretching.
3. The fluid transfer, musculoskeletal interaction as well as the internal organs experiencing inertial forces are neglected for the sake of calculation.
4. The masses beneath the seating position (legs, feet etc.) are omitted due to little or no role except absorbing forces via legs in a frontal crash.
5. Taking anecdotal observation from our driver physiology and harnesses used, we can conclude that driver can travel about 27^0 pivoted about his saccral region.
6. Taking initial velocity as 45km/h and final velocity zero we can apply Newton's equation of motion and calculate the inertial force acting on the occupant [14].

$$S= u*t+1/2 * a*t^2$$
$$a=39.24 \text{ m/s}^2 = 4g$$

7. This is the inertial force acceleration experienced by the body in frontal impact. This force corresponds to the acceleration experienced by the vertebrae interlinked with each other in a simulated crash of 4g acceleration. Since the momentum is conserved and according to the impulse momentum equation [14]:
8.

$$F_{avg}*\Delta t = m (v_2-v_1)$$

The foam inserts here serve three primary purposes in prevention and dissipation of F_{avg} during impulse generated in crash:

- Increase in time difference reduces peak F_{avg} loading on spinal vertebral columns, hence reducing chances of spine IVD dislocation, soft tissue rupture as well as preventing abrasion of vertebral bone sections
- The foam by virtue of its compressibility and adequate rebounding absorbs shock forces and deformation subtracts a fraction of force further minimizing the impact.
- The foam arrangement and attachment is such that it actively stiffens along its longitudinal cross section when the drivers' back is flexed more than 100^0.

The mass distribution of upper torso and abdominal region is taken as follows [11]:

Table 1.1

Region	Mass (kg.)
Head	4.51
Neck	1.01
Thoracial torso	17.75
Abdomen	3.76
Pelvis	9.75
Upper arm	2.71

The mass is then divided according to its proximity relative to each other and merged for the sake of calculation. These masses are then modelled as inverse pendulums and superimposed over each other to generate the model for dynamic analysis.

The time is calculated from Newton's second law of motion [14]:

$$S=u*t+0.5a*t^2 \;;$$

Therefore, assuming S = radius*angle, ($\phi=27^0$), u=45km/hr. and a = 4g we have t = 0.1 sec

The driver restrained and pivoted in his seat resembles an inverted pendulum, and hence the equations of motion for inverse pendulum is applicable here also, solved either by Lagrangian approach or Newtonian approach [15]; either way the final equation is the same, i.e.:

$$L * d^2\phi/dt^2 - g\sin\phi = d^2\phi/dt^2*\cos\phi$$

Derivation further reveals:

$$L*\phi = (4g\cos\phi+g\sin\phi)*t^2/2$$

Theoretical calculations based on the above assumptions and formulas are carried and compiled:

Cervical section:

S. no	Angle (⍰)	Angle (radians)	Time (t) sec	Angular velocity (rad/sec)	Radius (m.) (Length of section from pivot)	Linear velocity (m/sec)	Force (N)	Force (res.)
1.	0	0	0	-	0.625	-	-	-
2.	5	0.0873	0.0369	2.3649	0.625	1.4780	-	-
3.	18	0.2618	0.0626	6.7880	0.625	4.2425	413.5274	**417.05**
4.	27	0.4712	0.0821	10.7239	0.625	6.7024	528.1190	**530**

Thoracial:

S. no	Angle (⍰)	Angle (radians)	Time (t) sec	Angular velocity (rad/sec)	Radius (m.) (Length of section from pivot)	Linear velocity (m/sec)	Force (N)	Force (res.)
1.	0	0	0	-	0.445	-	-	-
2.	5	0.0873	0.0311	2.8026	0.445	1.2472	-	-
3.	18	0.2618	0.0528	10.9549	0.445	4.8749	2997.8	**3008.3**
4.	27	0.4712	0.0693	12.7091	0.445	5.6555	925.8	**9595**

Lumbar:

S. no	Angle (⍰)	Angle (radians)	Time (t) sec	Angular velocity (rad/sec)	Radius (m.) (Length of section from pivot)	Linear velocity (m/sec)	Force (N)	Force (res.)
1.	0	0	0	-	0.215	-	-	**-**
2.	5	0.0873	0.0216	4.0321	0.215	0.6026	-	**-**
3.	18	0.2618	0.0367	11.5734	0.215	2.3553	2388.2	**2405.6**
4.	27	0.4712	0.0482	18.2841	0.215	2.7324	737.5	**792.1**

The peak values for different sections are then recorded as follows:

Section of the spine	Peak force resultant (newton)
Cervical	528.1190
Thoracial	3008.3
Lumbar	2405.6
Saccral+coccyx	4290.8 (Calculated as vertical force adding $F_{suspension}+F_{bump}$)

These peak forces are then visualized Vis-a-Vis the cushioning and damping provided via the foam inserts, as well as the F_{avg} reduction due to time interval expansion. The foam inserts' force absorption is given by [14]:

$$\mathbf{F_{deformation} = Y*l/A*\Delta L}$$

This force depends upon the cross sectional area along the direction of compression, length as well as the length deformed during application of loads. Compressive strength along direction of rise is taken as 0.62 Mpa for FlexiPUF PU foam of density $62kg/m^3$ and cross section is taken as the length compressed during bottoming out of the foam in compression. Cervical section is omitted due to head rest, neck-roll and helmet providing hindrances in effective calculated forces.

Section of contoured padding	**Dimensions (mm)**	**Force absorbed ($F_{deformation}$)**	**Final forces (F_{res})**
Thoracial	100x300x35	160N	2848.3N
Lumbar	200x300x45	448N	1957.6N
Saccral+Coccyx	100x100x10	Negligible	4290.8N

The calculations were carried out in MATLAB:

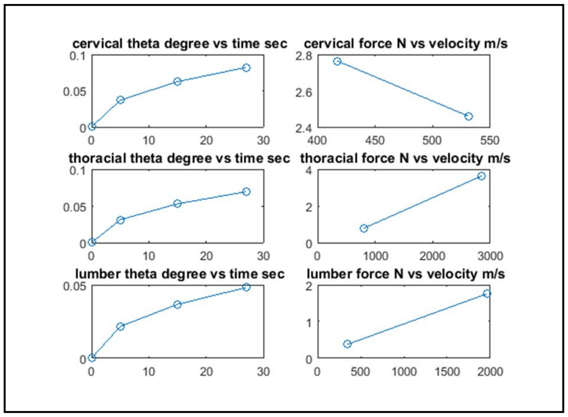

Fig 3: The results of the calculations carried out in MATLAB

Since the NIOSH determined maximum value of spinal axial loading is 6200N and 3600N in bending position, we see that there is considerable reduction in impact forces when the occupant is wearing the vest during harsh riding and experiencing 4g bumps in mid-air jumps.

9. SELECTION OF MATERIAL FOR DAMPING AND SHOCK ABSORPTION:

The material was to possess qualities like adequate rebound after compression, linearity in variation of stiffness, strong, durable, not overtly stiff as well as having considerable loading and unloading cycles during its lifetime. Young's modulus of foam must lie around 0.9 g/cm^3 (as well as it must be open cell so as to freely compress and decompress whilst attached in vest.) Hence a block of Flexi-PUF 60 kg/m^3 density foam was procured and was used as a billet for carving out profiled foam for cushion inserts in the vest.

10. FINAL PROTOTYPE AND DESIGN:

The final design was made according to a cocktail of various ideas, mockups and iterations based on driver feedback as well as matching them with calculated value. The vest consists of four parts:

1. The Profile contoured foam inserts
2. The reticulated fiber reinforced mounting vest
3. The Outer cushion cover made of RF material
4. Harnesses and restraints made of nylon

Profile contoured foam inserts:

1.1 The foam selected was a FlexiPUF 60 Kg/m^3 density polyurethane foam used in seat cushioning and upholstery. This foam was selected from various densities ranging from 23 Kg/m^3 to 100 Kg/m^3 and was selected due to adequate rebound, stiffness as well as prevention of bottoming out whilst still compressible enough to be comfortable for the driver. The foam is also intentionally different than the seat material for independence of functioning of two interfaces.

1.2 This foam was then cut and profiled according to anecdotal reference of driver spine and its position long his back. This is suitable for driver resembling global average male of 5’9’’ (172cms) and having spinal column. The thoracial and lumbar regions were targeted for support and efforts were made to restore normal positive Lordotic and kyphotic curves during normal seating posture and eliminate slouches.

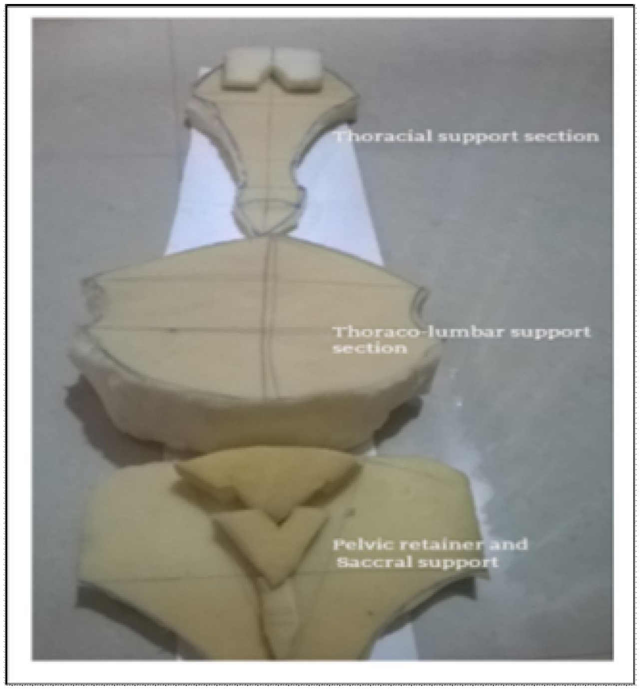

Fig 4: Foam arrangement before stitching, First being the thoracial support, second the thoracic-lumbar support and third the pelvic retainer and sacral support.

The reticulated fiber reinforced mounting vest:

2.1 The vest was made out of two layer rexin layered on top with reticulated synthetic coir type fiber layer to drain out water and debris as well as provide additional damping. It also has an aesthetic element to it suiting the off-road apparel and driver suit.

2.2 It acts like a platform on which the cushions are strategically mounted and secured by stiches.

The Outer cushion cover made of RF material:

This acts as a retainer for the foam and visually smoothens the outer profile. Also this prevents the protruded parts of the foam cushions to lock with the seat contours and generate additional strain on the back.

Harnesses and restraints made of nylon:
Harnesses are provided as per as the assumptions made in the calculations. A tight fitting and adjustable lap belt and two shoulder belts are provided to ensure that the driver may tighten the vest according to his comfort and periphery securing profile of vest.

11. INSTALLATION

The driver is first made to stand erect and the vest is then put on the driver, an assistant helping him to secure belts and harnesses around his body. The shoulder belts are first tightened and then the lap belt is secured until the lumbar section feels tight around his lower back. The vest is tightened to an extent so that the vest attains the shape of his vertebral column and this is verified visually. Any signs of oddity and discomfort are addressed and the vest is adjusted accordingly. The pelvic retainer is positioned on the driver's seat and then the driver sits on the seat with pelvic/sacral support inside. The safety 5 point harness is then attached.

12. CONCLUSION

This research paper aims to elaborate on the various measures available in the market for spinal safety and safe riding in harsh conditions for the driver in off road conditions. The paper proposes a viable solution in the form of a safety support vest which works on mimicking the spinal profile of the wearer. The vest, apart from the intended use in off-road adventure riding can also be modified and used by the elderly in public transport as well as the disabled and injured in normal riding or sitting conditions on seats and carriages not optimized for them. Future improvements are possible without compromising on the efficiency and utility of the prototype.

12. FUTURE IMPROVEMENTS

1. Addition of 3D printed back clamp and mounts to adjust the preload springs and driving posture
2. Incorporating Velcro instead of stiches to increase the adjustability and modularity
3. Introducing adjustable cushions and variable foam density options
4. Reduction in size and weight so as to make it wearable inside the driver suit.
5. Incorporating load cells to record real time data of spinal shocks and loading into the vest for optimization.

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