

Modelling of a Biomechanical Vertebral System for Seat Ejection in Aircrafts Using Lumped Mass Approach

R. Unnikrishnan, K. Shankar

Abstract—In the case of high-speed fighter aircrafts, seat ejection is designed mainly for the safety of the pilot in case of an emergency. Strong windblast due to the high velocity of flight is one main difficulty in clearing the tail of the aircraft. Excessive G-forces generated, immobilizes the pilot from escape. In most of the cases, seats are ejected out of the aircrafts by explosives or by rocket motors attached to the bottom of the seat. Ejection forces are primarily in the vertical direction with the objective of attaining the maximum possible velocity in a specified period of time. The safe ejection parameters are studied to estimate the critical time of ejection for various geometries and velocities of flight. An equivalent analytical 2-dimensional biomechanical model of the human spine has been modelled consisting of vertebrae and intervertebral discs with a lumped mass approach. The 24 vertebrae, which consists of the cervical, thoracic and lumbar regions, in addition to the head mass and the pelvis has been designed as 26 rigid structures and the intervertebral discs are assumed as 25 flexible joint structures. The rigid structures are modelled as mass elements and the flexible joints as spring and damper elements. Here, the motions are restricted only in the mid-sagittal plane to form a 26 degree of freedom system. The equations of motions are derived for translational movement of the spinal column. An ejection force with a linearly increasing acceleration profile is applied as vertical base excitation on to the pelvis. The dynamic vibrational response of each vertebra in time-domain is estimated.

Keywords—Biomechanical model, lumped mass, seat ejection, vibrational response.

I. INTRODUCTION

THE escape of pilot from high-speed aircrafts has led to the development of ejection seats, considering the safety of the pilot. During seat ejection, the pilot has to undergo heavy windblast due to the high speed of aircraft and has to experience very high G-forces that leads to the pilot's immobilization, which prohibits their escape.

The latest aircrafts employ rocket motors attached to the bottom of the seat, which utilizes the latest in technology to monitor several factors like altitude, velocity, etc. using sensors and decide the accurate ejection parameters as presented by Specker et al. [1]. Symmetriad Laerters IV is an example of Fourth Generation seat that is electronically controlled. It is designed for aircraft crews of practically any weight or build. The electronic controllers decide the ejection parameters on the basis of flight ergonomics, to minimise the

injury of the crew. The acceleration does not exceed the safe limits and allows ejection from reasonable levels of pitch and roll combination, at any altitudes and airspeeds.

The ejection forces due to the rocket motors mainly act in the upward vertical direction. The objective of this force is to attain the greatest possible velocity over a specific period of time. The force lies in the range of 12 and 20 Gs. Latham [2] states that the incidence of spinal injury tends to increase if the peak acceleration exceeds 25 Gs and the rate of onset is greater than 300 Gs per second.

The ejection process involves a sequence of events that subjects the human body to very high levels of forces. Several factors decide the acceleration force that has to be subjected on to the base of the seat. It will be influenced by the complex mechanical behaviour of the pilot's body in its relationship to the seat as well as how various body parts relate to each other. The rocket propelled seats have increased the duration of upward thrust and significantly reduced the rate of onset.

From very early designs [2], improper flexure of spine was recognized as one of the major contributing factors to spinal injuries during ejection and thus the proper alignment of the spine along the line of thrust is important to avoid injuries. Lam et al. [3] conducted a study on 22 ejectees from 18 aircrafts in the UK, out of which 5 had clear detectable compression fractures in the thoracic-lumbar region, but the majority had occult fractures which were not detectable by radiography. In another study, Fitzgerald and Crotty [4] estimated that the annual instance of major spinal fractures in UK ranged from 33% to 60% in the late 1960's which have diminished significantly in recent years. Their study shows that the most significant factor for fatality was the delay in deciding to eject.

In this paper, a simple and effective analytical model of the human spine is modelled. It can be used to study the effect of loads on vertebrae for different patterns of acceleration profiles.

II. MODEL

The vertebrae in the spinal column makes up a complex shaped structure whose mechanical behavior is not completely understood. Vertebrae is primarily divided into 3 regions, starting from the neck (cervical region) and going down there are 7 cervical vertebrae (C1-C7), followed by 12 thoracic vertebrae (T1-T12) and 5 lumbar vertebrae (L1-L5). Brodeur [5] states that the lumbar region is associated with lower back pain and is subjected to analysis. The main advantages of

R. Unnikrishnan and K. Shankar are with the Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai-600036, India (e-mail: unnikrishnanr91@gmail.com).

developing a bio-mechanical model is the ease of studying the mechanical response of spine under a wide variety of different load conditions which are difficult to obtain experimentally.

The human spine is mostly modelled as multi-body/discrete parameter models which are less complex compared to finite element models. Belytschko et al. [6] presented a linear 3-D model of the spine with pelvis, thorax and viscera. Kitai and Griffin [7] developed a 2-D finite element model, which was used to find out the human biomechanical responses to whole body vibrations. The spine, head, pelvis, buttock tissues and the intervertebral discs in the mid sagittal plane were modelled as mass and spring elements [7].

Ramm and Kaleps [8] have formulated the equations of the ejection process by considering the seated body as a simple 2 degree of freedom model with the head and torso considered as 2 lumped masses connected by an elastic spring. The primary aim was to estimate the initial conditions for the impulse required to obtain safe ejection time, which should be less than the critical time.

Latham [2] through a series of experimental studies on the spine, established the limits of safe acceleration and the acceleration rates. The examination of intersegment displacement-time profiles obtained during the application of manually assisted mechanical thrust forces to the lumbar spine suggests the value of damping ratio to be up to 30% of critical value.

III. SAFE EJECTION PARAMETERS

The safe ejection parameters: Ejection time required to safely eject the crew from flight and the acceleration required for safe ejection, are estimated. The ejection time is calculated keeping in consideration the fact that, by the time the pilot moves horizontally to the position of the tail of the aircraft, he should have achieved a vertical displacement greater than the height 'H' of the tail of the aircraft. The acceleration pattern 'a(t)' is calculated with the objective of minimizing the deformation of the pilot's spine.

Considering an aircraft of length 'L' moving with constant velocity 'V' flying at a constant altitude. It is assumed that there are no vertical movements and the pilot is rigidly strapped on to the seat. The upper part of the body is fixed to the lower torso by an elastic-damping mechanism. Biologically, this connection is done by the spine of the pilot.

The acceleration is applied over a time period $[0, t_0]$, where $a(t) = 0$ for $t > t_0$. The pilot and the seats move in the vertical direction due to the influence of the applied force during the period $[0, t_0]$ and afterwards their motion is governed by the gravitational force and the initial conditions at $t = t_0$. The motion of the pilot in the horizontal direction is governed by:

$$\dot{v} = -bV^2 \quad (1)$$

where, $b = \frac{1}{2m} C_d \rho A$; C_d = Coefficient of drag of average man in seated posture=1; ρ = Density of air = 1.202 kg/m^3 ; A = Frontal area of average man in seated posture = 0.8 m^2 .

The governing equation can be solved analytically by,

$$v(t) = \frac{V}{1 + bVt} \quad (2)$$

The relative velocity of the pilot in the coordinate system with respect to the aircraft is,

$$v - V = -\frac{bV^2 t}{1 + bVt} \quad (3)$$

Considering the critical time of ejection as t_c , the inequality $t < t_c$ is necessary for the pilot to clear the tail of the aircraft during the ejection process.

Let T be the time required for the pilot to traverse L ,

$$T = \frac{L}{V} = [t_c - \frac{1}{bV} \ln(1 + bVt_c)] \quad (4)$$

We assume, $bVt_c = Z$ and $bVT = Z_T$. The equation simplifies to,

$$\phi(Z) = Z - \ln(1 + Z) - Z_T = 0 \quad (5)$$

where, $Z = f(C_d, m, V, t_c)$.

Solving (5), would yield the values of critical time of ejection for various geometries and velocities of aircraft.

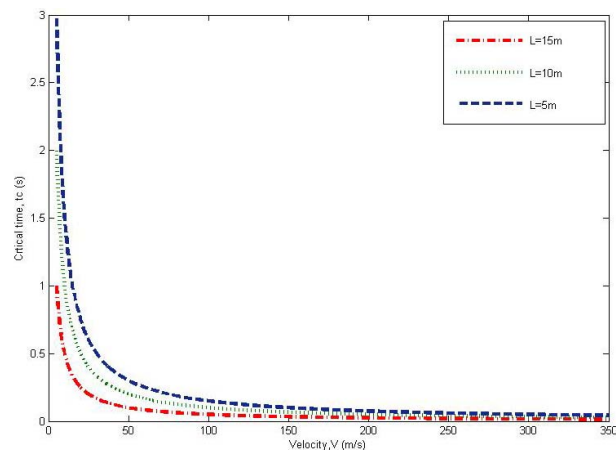


Fig. 1 Critical time vs Velocity of flight

It can be seen from Fig. 1 that as the length between the cockpit and tail of the flight increases the critical time of ejection also increases. The velocity of flight is also an important criteria in the ejection time.

The ejection process is usually not carried out in the extreme velocity range. The scope of this work is limited to normal fighter aircrafts having length between the cockpit and the tail, in the range of 10-15 m. The critical time of ejection, $t_c = 0.25 \text{ s}$ is taken for the further scope of the study.

For covering a vertical distance H with uniformly increasing acceleration, the equations of motion for acceleration, velocity and displacements are given by:

$$a = k_0 t$$

$$v = \frac{k_0 t^2}{2}$$

$$H = \frac{k_0 t^3}{6}$$

Fig. 2 plots the acceleration profile for different heights of the tail of the flight for a time period of 0.25s. The spinal responses in the form of compression of intervertebral discs are found out by applying this acceleration profile onto the base of the model.

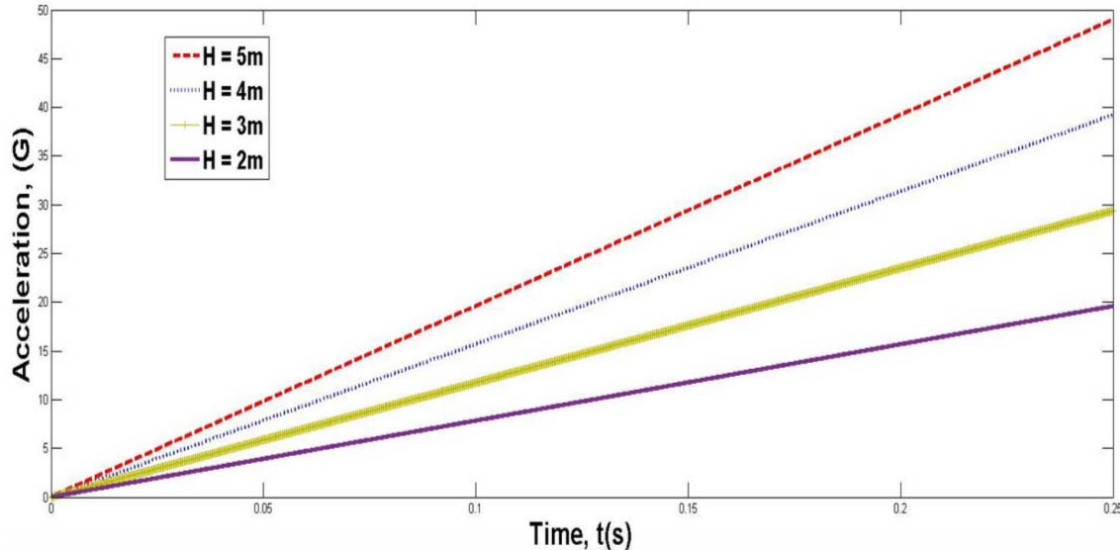


Fig. 2 Linearly increasing acceleration profiles for different heights of the aircraft tail

TABLE I
TRANSLATIONAL AND ROTATIONAL MASSES OF SPINE

Level	TM [*] (kg)	RM [*] (kgm ²)	Level	TM [*] (kg)	RM [*] (kgm ²)
Head	4.5	2	T6	1.948	0.4425
C1	0.815	0.0601	T7	1.308	0.5374
C2	0.815	0.0601	T8	1.326	0.5543
C3	0.815	0.0601	T9	1.417	0.6164
C4	0.815	0.0601	T10	1.352	0.6028
C5	0.815	0.0601	T11	0.3184	0.1283
C6	0.9	0.0656	T12	0.3329	0.1270
C7	1.2	0.0775	L1	0.2842	0.1036
T1	2.114	0.0745	L2	0.3420	0.1253
T2	1.829	0.2077	L3	0.4325	0.1482
T3	1.915	0.2878	L4	0.5621	0.1427
T4	1.819	0.3138	L5	0.4659	0.0993
T5	1.93	0.3838	Pelvis	16.877	14.13

^{*}TM- Translational Mass

^{*}RM- Rotational

IV. BIOMECHANICAL VERTEBRAL SYSTEM

The human vertebrae vary in their size. The cervical vertebrae are the smallest, lumbar vertebrae are the largest and the thoracic vertebrae have intermediate size. They are the load bearing structures of the spinal column. The upper body weight is distributed through the spine to the sacrum and pelvis. The vertebrae are composed of lots of critical elements that contribute towards the overall function of the spine, which includes the intervertebral discs and facet joints.

The 2D model, developed by Kitai and Griffin [7], consists of 24 flexible bodies representing all the intervertebral discs between the vertebrae C1 and the sacrum S1. Each spinal disc

was placed between the geometrical centers of the adjacent vertebral bodies and was given the axial and bending stiffness's of the disc. The discs were considered as massless elements. The head was modelled as a mass element and connected to the top of the cervical vertebra C1 by a disc representing the Atlanto-occipital joint. The pelvis was again modelled as a mass element and connected to the bottom of the spine. The elemental masses and geometric parameters of the models were determined from the model parameters used in literature [7].

The moment of inertia of each vertebral body is calculated by parallel axis theorem assuming that the vertebral masses are all rigid and connected rigidly to each other. Each vertebral mass is connected to one another by discs. These discs are simply composed of a linear translational spring-damper and a linear rotational spring-damper.

The intervertebral ligaments and articular facet interactions were not included, as no reliable data were available in the literature.

The stiffness data for the spinal discs were based on the stiffness values between the intervertebral discs and the atlanto-occipital joint estimated by Williams and Belytschko [10].

No elemental damping was incorporated in the present model because no reliable data were available. The damping effect was accounted through the use of modal viscous damping ratios. Kellar [11] suggested that the damping ratios can up to 30% of critical value. In the analysis the modal damping ratios for each segment were assumed to be identical. The damping matrix C is expressed as a linear combination of

mass matrix M and stiffness matrix K , assuming Rayleigh's proportional damping model as:

$$C = \alpha M + \beta K \quad (6)$$

The values of α and β were estimated as 19.475 and 2.65×10^{-3} respectively.

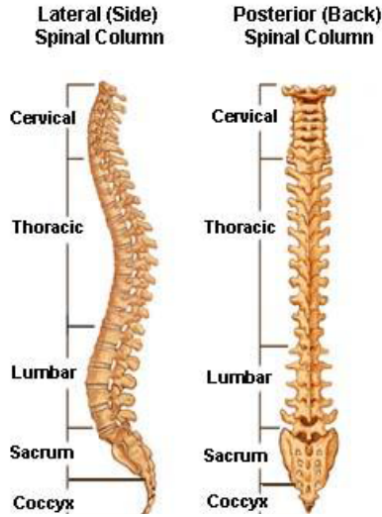


Fig. 3 Human Spinal Column [9]

Vertebrae primarily consist of cancellous bone, an isotropic viscoelastic material. Generally the elastic moduli and strength of bone is proportional to the square of the density of bone. For normal, healthy adults the absolute failure load increases from the cervical region to the lumbar region, mainly because of the increasing size of the vertebrae. The cancellous bone is enveloped by a more rigid layer of cortical shell.

TABLE II
AXIAL AND ROTATIONAL STIFFNESS OF INTER-VERTEBRAL DISCS

Level	k_x^*	k_θ^+	Level	k_x^*	k_θ^+
Head-C1	0.55	4	T6-T7	1.8	7
C1-C2	0.33	9	T7-T8	1.5	7
C2-C3	0.7	0.8	T8-T9	1.5	7.7
C3-C4	0.76	1	T9-T10	1.5	7.7
C4-C5	0.794	1.2	T10-T11	1.5	8.4
C5-C6	0.967	1.6	T11-T12	1.5	7
C6-C7	1.014	2.2	T12-L1	1.8	6.3
C7-T1	1.334	3.7	L1-L2	2.13	6.3
T1-T2	0.7	1.4	L2-L3	2	6.3
T2-T3	1.2	2.8	L3-L4	2	6.3
T3-T4	1.5	4.2	L4-L5	1.87	5.6
T4-T5	2.1	7	L5-S1	1.47	0.7
T5-T6	1.9	7	-	-	-

* k_x - Axial stiffness (N/m* 10^6)

+ k_θ -Bending Stiffness (Nm/rad* 10^2)

V. LUMPED MASS ANALYSIS

The 24 vertebrae in addition to the head and pelvis were represented as 26 rigid structures and the intervertebral discs were assumed as 25 flexible joint structures. The equations of

motion are derived for each vertebral element from the free body diagram by the application of Newton's second law.

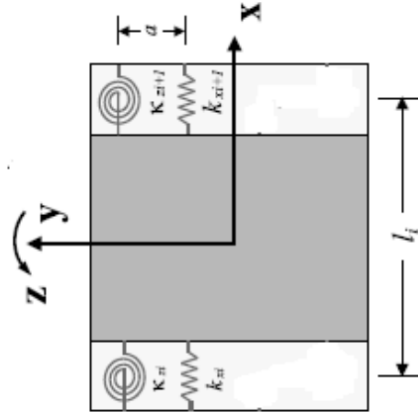


Fig. 4 Vertebral body and intervertebral disc

The spring force acting on the i^{th} vertebra is given by:

$$F_{xi} = k_{xi}[(X_i + \theta_i a_i) - (X_{i-1} + \theta_{i-1} a_{i-1})] - k_{xi+1}[(X_{i+1} + \theta_{i+1} a_{i+1}) - (X_i + \theta_i a_i)] \quad (7)$$

where, k_{xi} is the axial stiffness of i^{th} intervertebral disc and a_i is the spring axis constant. The spring constant values are all equal and negligible. The modified spring force equation on the i^{th} vertebra is given by:

$$F_{xi} = k_{xi}[(X_i) - (X_{i-1})] - k_{xi+1}[(X_{i+1}) - (X_i)] \quad (8)$$

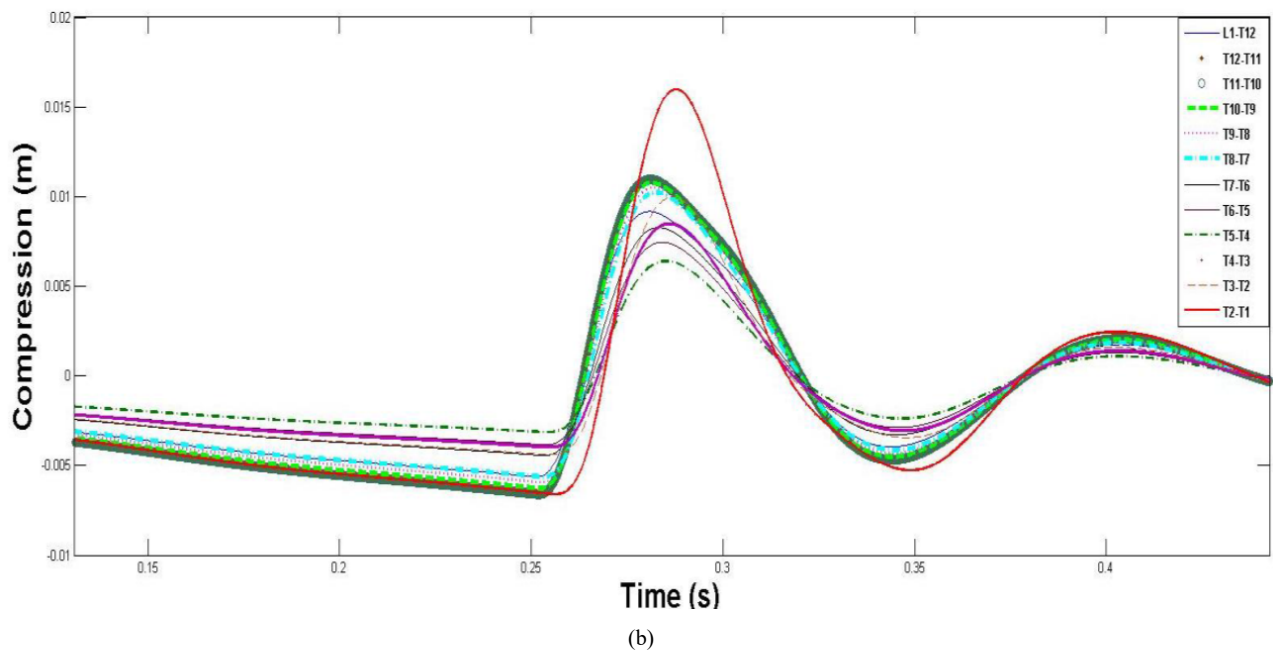
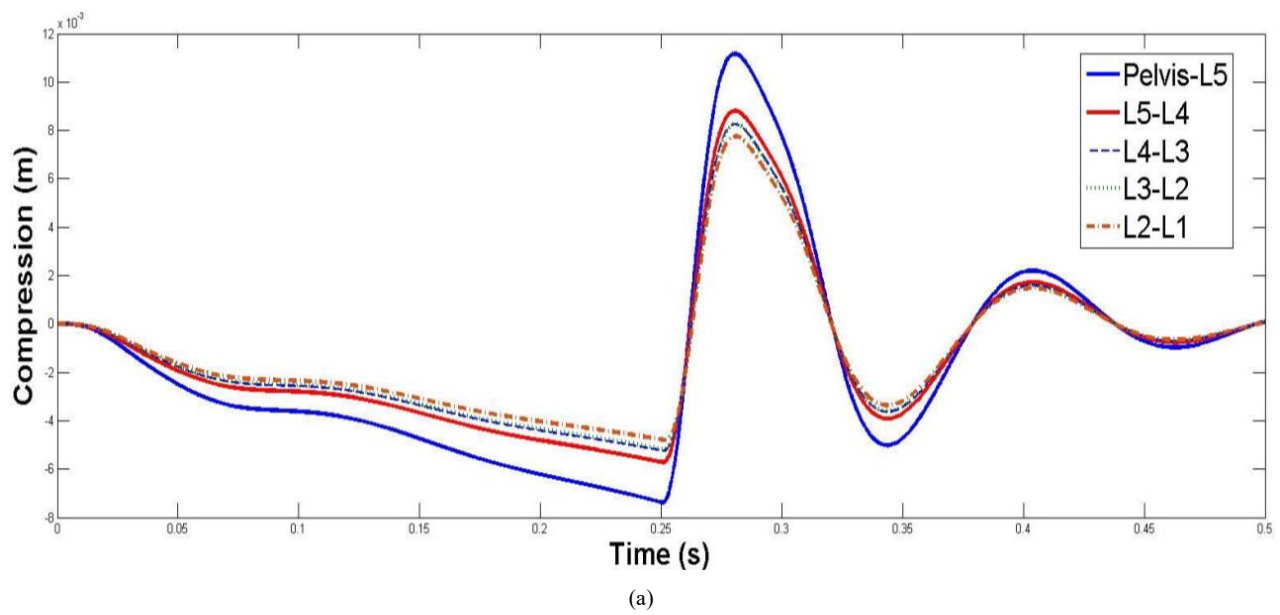
The lumped mass system generated is then solved with the base excitation acceleration profile estimated from safe ejection parameters.

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = -[I][M][a] \quad (9)$$

The above set of equations is solved by the Newmark-Beta method in MATLAB to obtain the displacement, velocity and acceleration vectors.

The base excitation force is applied in the form of linearly increasing acceleration, for the same duration as the critical time of ejection. It is observed that the compression primarily occurs in the cervical region of the spine owing to the low values of stiffness of intervertebral discs in that region. The highest compression occurs between the C1 and C2 vertebrae, which can be accounted to the very high mass of the head attached to the C1 vertebra. The lumbar region is found out to have the least compression of intervertebral discs as they have higher stiffness values compared to other vertebral regions.

The force is observed to be higher in the thoracic region with the highest force acting on the T1 vertebra. Even though the compression values of the intervertebral discs were higher in the cervical region, the vertebrae in this region has got the lowest forces acting on them. This is mainly because of the low stiffness values associated with them.



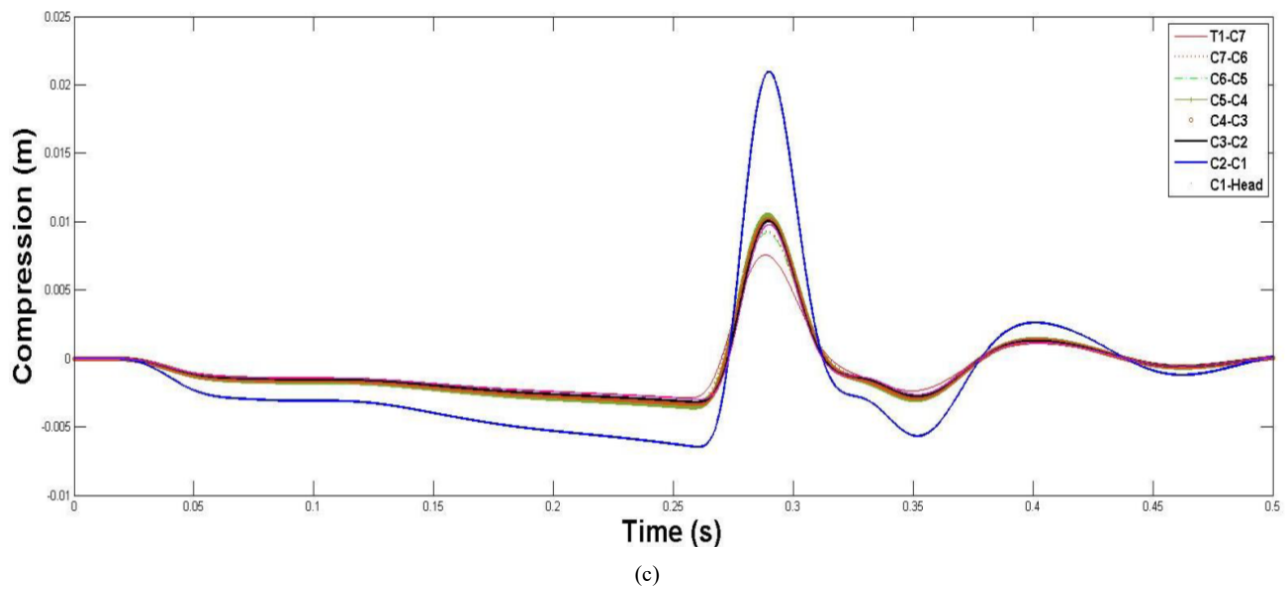
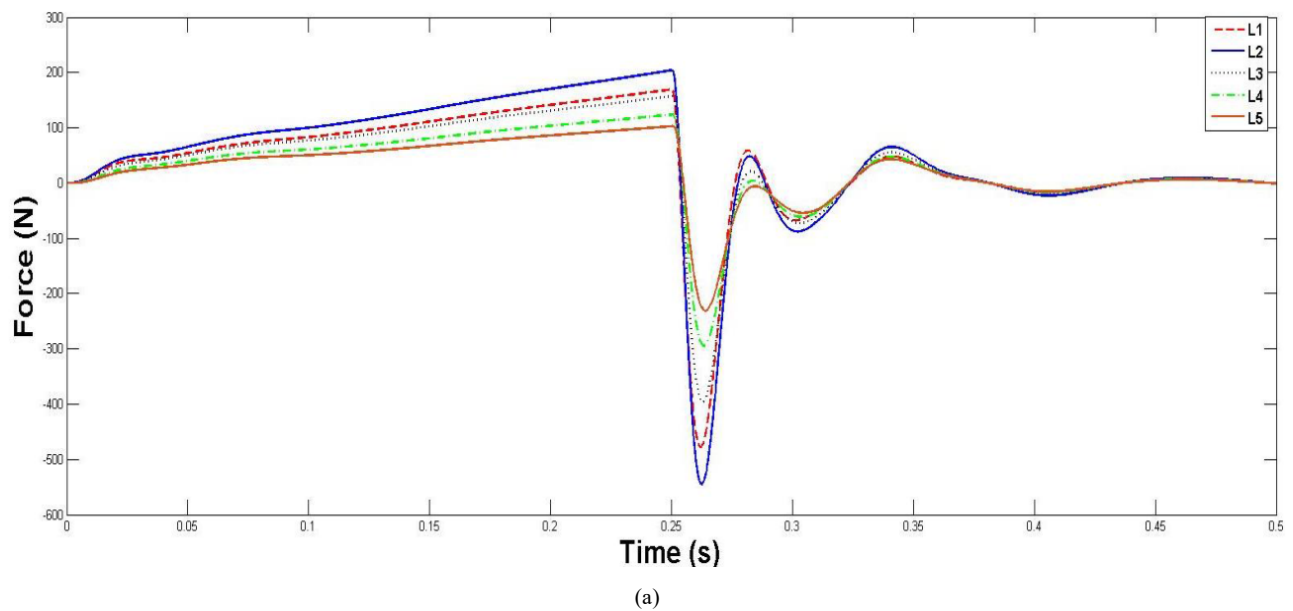
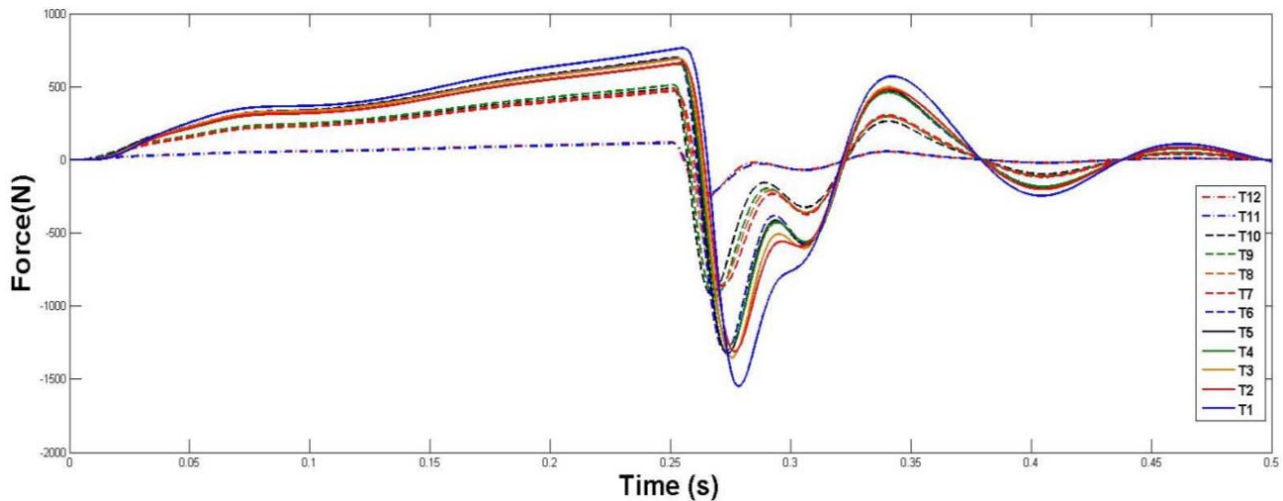
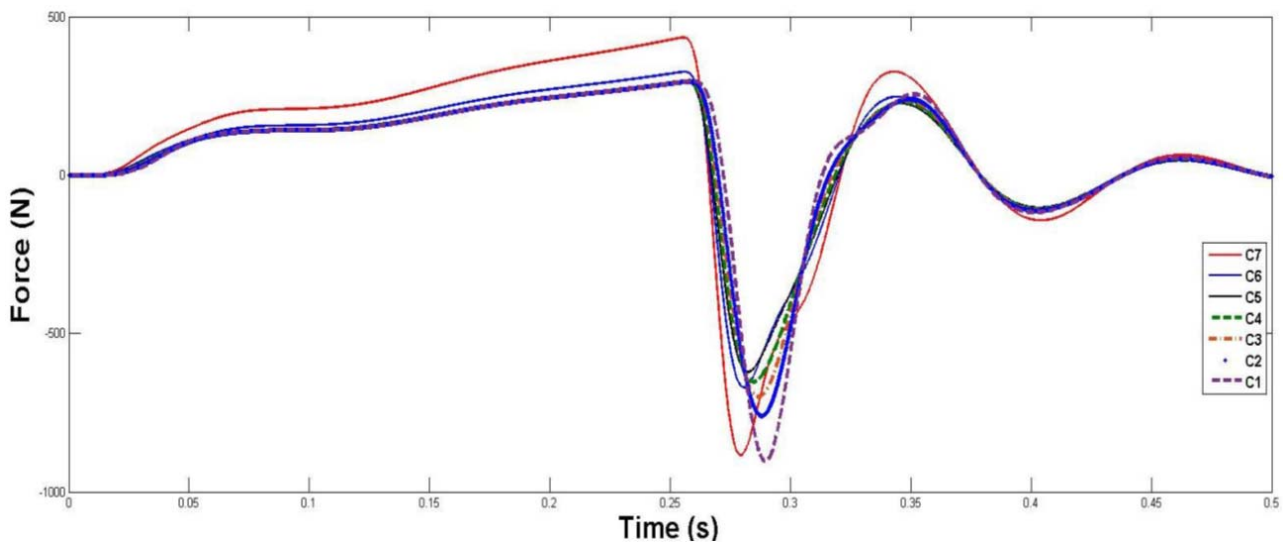


Fig. 5 (a), (b) and (c) Compression of intervertebral discs between lumbar, thoracic and cervical vertebrae





(b)



(c)

Fig. 6 (a), (b) and (c) Force acting on the lumbar, thoracic and cervical vertebrae

REFERENCES

- [1] Larry Specker, John Plaga and Vic Santi, "Ejection Seat Capabilities to Meet Agile Aircraft Requirements", *Air Force Research Laboratory TR-015-09*, pp. 121-129, 2001.
- [2] S. Latham, "A Study in Body Ballistics: Seat Ejection", *Proc. Royal Soc. Of London Series B. Biological Sciences*, 147 (926), pp. 121-139, 1957.
- [3] K. S. Lam, R. W. Kerslake, J. K. Webb, "High incidence of Occult Spinal Injuries following Vertical Aircraft Ejection: A Prospective Study Using Magnetic Resonance Imaging", *Journal of Bone and Joint Surgery*, 87B (240), pp. 240-253, 2004.
- [4] Fitzgerald A. G. and Crotty J., *RAF Institute of Aviation Report No. 505*, 1971.
- [5] Raymond R. Brodeur, Mac Reynolds, "Modeling Spine Shape for Seated Posture", *Report No. ERL-TR-95-007, Ergonomics Research Laboratory, Michigan State University, USA*, 1995.
- [6] Belytschko T., L. Schwer, A. Schultz, "A Model for Analytic Investigations of Three-Dimensional Head-Spine Dynamics", *AMRL-TR-76-10*, 1976.
- [7] Kitazai and M. J. Griffin, "A model analysis of whole body vertical vibration, using finite element model of human body", *Journal of Sound and Vibration*, vol. 200(1), pp. 83-103, 1997.
- [8] A. G. Ramm and I. Kaleps, "Modeling the Ejection Process", *Mathematical Computer Modeling*, 20 (1), pp. 95-101, 1994.
- [9] <http://drcaram.com/spinal-anatomy-overview>
- [10] J. L. Williams and Belytschko T., "A Three Dimensional Model of the Human Cervical Spine for Impact Simulation", *Journal of Biomechanical Engineering (ASME trans.)*, 105 (4), pp.321-331, 1983.
- [11] Tony S. Keller, "Force-deformation response of the lumbar spine: a sagittal plane model of posteroanterior manipulation and mobilization", *Clinical Biomechanics* vol. 17, pp. 185-196, 2002.