On the importance of the forces and moments at the occipital condyles in predicting ligamentous cervical spine injuries

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Abstract Severe loading experienced in automotive crashes can cause ligamentous neck injuries. The Anthropomorphic Test Devices measure neck injury metric (Nij) using force and moment at the upper neck load cell. Recent discussions have focused on the adequacy of just the axial force at occipital condyles (OC), without the knowledge of moment at OC, in predicting neck injuries. This study aims to elucidate this issue by conducting a parametric simulation study using Global Human Body Models Consortium (GHBMC) 50th percentile male model under impact conditions (sagittal motion only), and evaluating strains in the cervical spine ligaments. Neck injuries were also studied in frontal sled tests with PMHS (Post Mortem Human Subjects) and frontal crashes in CIREN (Crash Injury Research and Engineering Network) database to investigate the type of ligamentous injuries in automotive crashes. Simulation results showed that OC axial force correlated well with strain in most of the ligaments, however, for some ligaments strain correlated better with OC moment. Field data analysis showed that ligamentous injuries can encompass a range of ligaments, therefore it was not possible to isolate force alone as the best predictor. Thus, both the OC axial force and moment are necessary for predicting ligamentous neck injuries.

Keywords Cervical spine, Finite Element, Human model***,*** Ligamentous injuries, Parametric study

I. INTRODUCTION

Cervical spine is the most frequently injured region of the spine in automotive crashes [1-2]. The cervical spine is supported by an extensive network of ligaments, which aids in joint stability and plays an important role in limiting the range of motion in the neck. These ligaments provide a significant contribution to the dynamic response of the neck in automotive crashes [3]. The ligaments serve various functions, such as allowing for proper motion of the vertebrae and, along with the muscles, providing stability for the spine [4]. Cervical spine injuries can vary from bony fractures to soft tissue injuries such as intervertebral disc disruption and ligament tear. This paper focuses on evaluating ligamentous injuries that may lead to other serious cervical spine disorders.

Crash tests are used to improve vehicle safety and to evaluate the injuries caused after a crash. Existing National Highway Traffic Safety Administration (NHTSA) regulations specify neck injury criteria as part of a comprehensive crash protection safety standard used in assessment of advanced restraint systems [5-6]. The neck injury criteria (Nij) proposes critical limits for all four possible modes of neck loading: tension or compression combined with either flexion (forward) or extension (rearward) bending moment. The Nij is defined as the sum of the normalized loads and moments, i.e.,

$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \quad (1)$$

where F_Z is the axial load, M_Y is the flexion/extension bending moment, and F_{int} and M_{int} are the critical intercept values of load and moment used for normalization [5]. The Anthropomorphic Test Devices (ATD) designed to measure the risk of injuries in automotive crashes, such as Hybrid-III and THOR (Test device for Human Occupant Restraint), have 6-axis upper neck load cell that dynamically records forces and moments in all three directions, which are then used to compute the neck injury metric Nij.

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The motivation for the Nij criterion originated from paired tests with animal models and ATDs, when it was suggested that combined tension and bending moments was a better predictor of injury in those tests than tensile forces alone [7]. However, recent discussions among researchers [8] have focused on the adequacy of just the axial force at the occipital condyles (OC) in predicting neck injuries. We hypothesize that both the axial force and moment at the OC are necessary for predicting neck injuries. Although other neck injury criteria have been proposed at times, such as NIC (based on head/T1 relative acceleration and velocity), Nkm (based on dynamic loads at OC similar to Nij) and NDC (head/T1 displacement-based criteria), for this study only the components (axial force and bending moment) of Nij (NHTSA regulated neck injury criteria) were considered to evaluate their applicability in ATDs for predicting neck injuries.

Computational models such as the detailed/validated human finite element (FE) models have become a popular tool to study not only kinematics but also tissue deformation and injury prediction. Ligamentous cervical spine FE models have been used in the past to analyze the effect of material properties of the ligaments on spinal kinematics [9-11]. Cervical spine FE models have also been used to study the effect of ligaments on cervical spine stability [12-13]. Full ATD multibody models i.e. EuroSID-2 with discretized neck have been used to study the utility of numerical models in understanding the kinematics of the cervical spine [14]. Although many computational studies, as noted above, have been conducted to investigate the cervical spine ligaments, no computational study has been carried out, to our knowledge, to correlate strains in the various cervical spine ligaments with biomechanical parameters like forces and moments. While limited experimental studies have analyzed the strains in the various cervical spine ligaments under simulated frontal and rear impact conditions [15-16], these studies did not correlate the ligament strains to the forces and moments at the OC.

The aim of this study is to analyze the correlation of strain in the various cervical spine ligaments with the axial force and bending moment at the OC using a computational approach, and test our hypothesis that both axial force and moment at the OC are necessary for the prediction of ligamentous neck injuries.

II. METHODS

Both computational and field/PMHS (Post Mortem Human Subjects) data analysis were conducted to investigate ligamentous cervical spine injuries. Computational modeling and simulations were carried out using the LS-DYNA [17] based 50th percentile adult male GHBMC (Global Human Body Models Consortium) v4.4 FE human model [18] which includes detailed representation of the cervical spine. An impact based parametric simulation study was conducted using the GHBMC model in the sagittal plane. In addition to the computational work, the various cervical spine ligaments that can fail in automotive crashes were evaluated using field data of frontal crashes from the CIREN (Crash Injury Research and Engineering Network) database and frontal sled tests with PMHS.

Computational Modeling

The neck model of the 50th percentile GHBMC human model contains 265,896 elements including 205,444 hexahedral solids, 55,991 shells, and 4,461 1D axial elements. The neck model is well validated at both the component level (tension compression, flexion/extension under both non-injurious loading and traumatic loading) and at the full neck level under a range of loading conditions (lateral, frontal and rear impacts). The model consists of seven cervical vertebrae, intervertebral discs, detailed facet joints, ligaments, 3D passive muscle, and 1D active muscle (Fig. 1). In addition to these components, the model also consists of a shell structure on the anterior of the neck to represent the volume filed by the trachea, cartilage etc. The intervertebral discs are modeled in details with representations for the annulus fibrosis ground substance, nucleus pulposus, and fiber lamina. The facet joints are modeled with the articular cartilage and a squeeze-film model to simulate the synovial fluid. A total of 26 neck muscles are modeled using solid elements for the passive response with embedded Hill-type 1D elements to simulate the active response. Ligaments are represented using multiple nonlinear rate dependent beam elements (Fig 2).

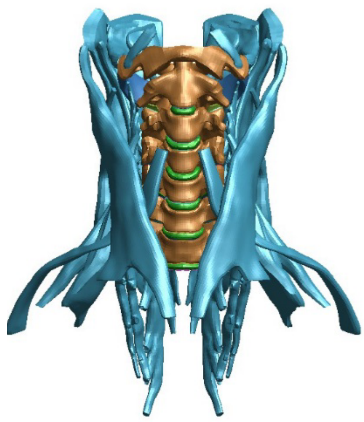

Fig.1. GHBMC neck model [19-22]

Multiple beam elements are used to distribute the load to the vertebral bodies and to allow for progressive failure of the ligaments [20]. The material properties for the ligaments are taken from literature [23-24] and LS-DYNA Material model 074 (*MAT_ELASTIC_SPRING_DISCRETE_BEAM) [17] is used for all the beam elements defining the ligaments with failure defined using the Tensile Displacement at Failure (TDF) parameter available in the material model. No changes were made to the material properties or the predefined TDF values of the ligaments in this study.

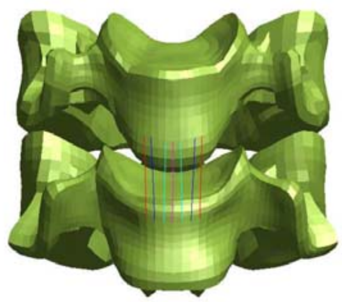

Fig. 2. Anterior longitudinal ligament at C4-C5 spinal level modeled with a series of discrete beams.

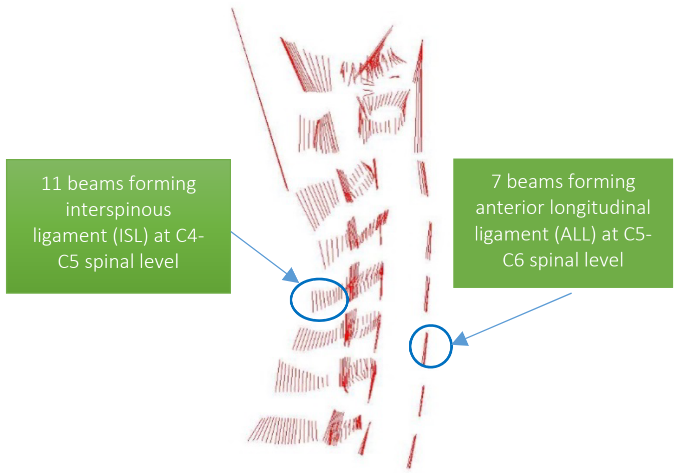

Fig. 3. The 895 beam elements that define the 45 cervical spine ligaments

The number of beam elements used to represent each ligament varies depending on the physical size of the ligament and the mesh density of the vertebral bodies which controls the number of attachment points for the beam elements. There are a total of 895 beam elements representing the various cervical spine ligaments (Fig. 3). These 895 beam elements are grouped into 45 cervical spine ligaments in accordance with the location and type of ligament. Two examples of grouping are shown in Fig. 3. These 45 cervical spine ligaments are further grouped under two main categories: primary cervical spine ligaments and craniovertebral ligaments.

The primary cervical spine ligaments (Fig. 4), namely the anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), ligamentum flavum (LF), interspinous ligament (ISL), and the capsular ligaments (CL) are present at most spinal levels. The craniovertebral ligaments (Fig. 5) are connected to the two vertebras C1(atlas) and C2(axis), and to the occipital bone of the skull. The two most prominent and important craniovertebral ligaments are the transverse and alar ligaments [25]. In addition to these two ligaments, other significant craniovertebral ligaments analyzed in this study were the anterior atlanto-occipital (AA-OM) and atlanto-axial membranes (AA-AM), posterior atlanto-occipital (PA-OM) and atlanto-axial membranes (PA-AM), superior (upper) and inferior (lower) cruciate ligaments (also known as crux), tectorial membrane and apical ligament.

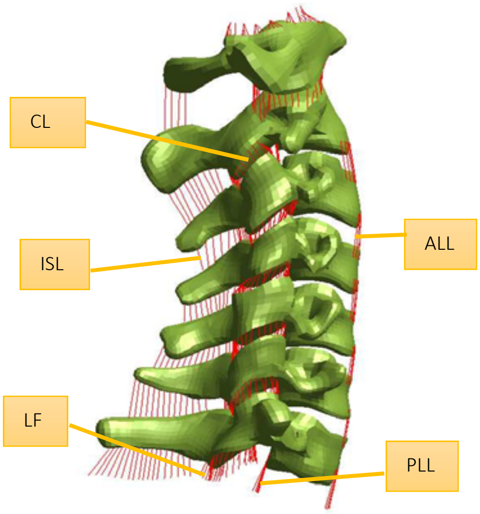

Fig. 4. Primary cervical spine ligaments

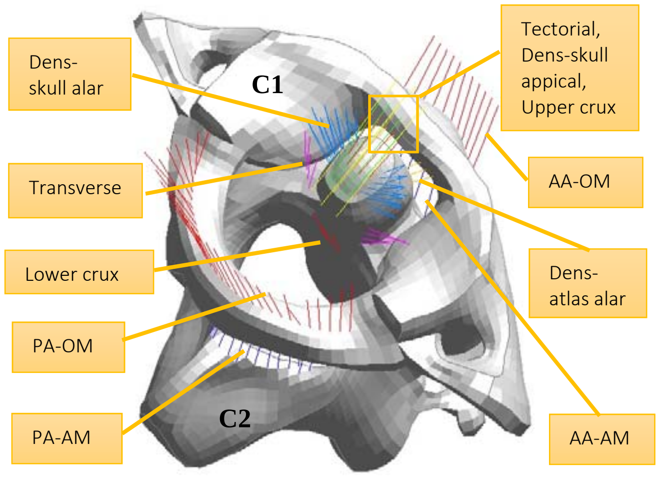

Fig. 5. Craniovertebral ligaments

Three ligaments, namely the supraspinous ligament (SSL), the intertransverse ligament (ITL) and the nuchal ligament (NL), were not analyzed in this study. The supraspinous and the intertransverse ligaments are not defined in the GHBMC model. The nuchal ligament is defined in the GHBMC model but it does not contribute to kinematic response and it is difficult to test its mechanical properties [24]. As a result, no TDF is defined for it in the model and thus this particular ligament was also excluded from this study. The 44 ligaments formed from the 890 beam elements (excluding five beams of nuchal ligament) are shown in Table I.

TABLE I
890 BEAM ELEMENTS GROUPED INTO 44 CERVICAL SPINE LIGAMENTS BASED ON TYPE AND LOCATION

Primary Ligaments	Primary Ligaments	Primary Ligaments	Craniovertebral Ligaments
C2-C3 ALL	C6-C7 ISL	C5-C6 LF	AA-AM
C3-C4 ALL	C7-T1 ISL	C6-C7 LF	AA-OM
C4-C5 ALL	C2-C3 PLL	C7-T1 LF	PA-AM
C5-C6 ALL	C3-C4 PLL	OC-C1 CL	PA-OM
C6-C7 ALL	C4-C5 PLL	C1-C2 CL	DENS-SKULL ALAR
C7-T1 ALL	C5-C6 PLL	C2-C3 CL	DENS-ATLAS ALAR
C1-C2 ISL	C6-C7 PLL	C3-C4 CL	DENS-SKULL APPICAL
C2-C3 ISL	C7-T1 PLL	C4-C5 CL	UPPER CRUX
C3-C4 ISL	C2-C3 LF	C5-C6 CL	LOWER CRUX
C4-C5 ISL	C3-C4 LF	C6-C7 CL	TRANSVERSE
C5-C6 ISL	C4-C5 LF	C7-T1 CL	TECTORIAL

Parametric study

A parametric simulation study was conducted using LSTC's LS-OPT [26] software to study the correlation between the axial force and moment at the OC with strains in the various cervical spine ligaments (Table I). Set-up of the impact simulations is shown in Fig. 6. All degrees of freedom of the pelvis were constrained. Head impacts were simulated with the help of a linear impactor to induce sagittal plane head-neck motion. The impactor was modeled with a rigid base with padding attached to the base via common nodes. Padding and rigid base were defined with solid elements. Elastic material model was used for the padding. In addition to the rigid base and padding, a null shell part was created at the front end of the padding for defining contact with the GHBMC model. All degrees of freedom of the impactor were constrained except X-translation and the motion was specified using initial velocity. The simulations were run for 60ms.

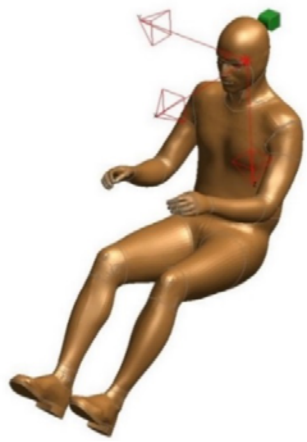

Fig. 6. Simulation set-up

Four impact parameters were varied: impactor mass, velocity, stiffness, and impact direction. A total of 32 cases were simulated (Table II). The simulations were carried out using commercial explicit finite element program LS-DYNA 971 [17].

TABLE II
VARIABLES FOR PARAMETRIC SIMULATIONS

Impactor mass (Kg)	Impactor velocity (m/s)	Impactor location	Impactor stiffness (MPa)
5	5	Forehead	5
7	7	Occiput	20
	9		
	11		

For the head impacts simulated in this study, primary motion occurs in the sagittal plane and thus the important measurements for Nij associated with sagittal plane motion are the axial load (Fz) and the flexion/extension bending moment at the OC (My). The axial load (Fz) and Moment (My) were obtained from the cross-section defined at the OC level in the GHBMC model. Strains were also computed for the 44 ligaments. As strain in the beam elements is not directly available as output from LS-DYNA, a python code was written to compute the strains. To obtain the ligament strains the following was carried out:

a. the X, Y and Z coordinate time history of all 890 beam element nodes was extracted from the NODOUT file;
b. the length, change in length and strain of each of the beam elements was computed as a function of time;
c. the maximum strain in tension was computed for each beam element;
d. for each ligament, the strain was computed as the maxima of the maximum strain in the beam elements forming that particular ligament. For example, the strain in the ALL at C5-C6 spinal level which is formed from seven beam elements will be the maxima of the maximum strains in the seven beam elements.

In addition to the measurements above, the following additional details were analyzed:

i. For each impact type (flexion and extension), the ligaments where high strains occurred were identified. To accomplish this, the following was done:
    - all simulations (32) were sorted based on the two impact types (flexion and extension);
    - for each simulation, the 44 ligaments were sorted based on strain to identify ligaments with the top three strains;
    - the ligaments which most frequently showed up in top three were identified for each impact type.
ii. In addition to individually evaluating strain correlations with OC force and moment for the dens-skull and dens-atlas alar ligaments, a combined strain correlation analysis was carried out, wherein the maxima (MAX_ALAR) of the maximum strain in dens-skull and dens-atlas alar ligaments was taken, and

the correlation of this maxima was evaluated with the axial force and moment at the OC.

The axial force (Fz) and the flexion/extension bending moment (My) at the OC were extracted along with the strains in each of the 44 ligaments for each simulation. These were used to generate the correlation matrix in LS-OPT [26].

CIREN and PMHS data analysis

To put the results of the parametric study into context, the various ligaments that fail in the automotive crash environment were studied using the CIREN database, as well as sled testing with PMHS. NHTSA's CIREN program dataset is a convenience sample of seriously injured occupants who were admitted to a Level I trauma center. CIREN contains detailed hospital and medical imaging data and conducts medical/engineering expert team review to assign sources, causes, and mechanisms of injury. For this analysis, a query of belt and airbag restrained first row occupants sustaining AIS 2+ cervical spine injuries in frontal crashes was performed. Frontal crashes were broadly defined for this query, and included crashes with principal directions of force 11 o'clock, 12 o'clock and 1 o'clock, along with any amount of frontal overlap. Within this sample, the presence and level of associated ligamentous injury was ascertained. We specifically focused on ligamentous injury associated with an Abbreviated Injury Scale (AIS) severity 2+ cervical spine injury because we wished to study injury metrics that would be assessed with ATDs in crash tests.

In addition to the CIREN cases, frontal sled tests conducted with PMHS were reviewed to assess AIS 2+ cervical spine and associated ligamentous injury. Numerous conditions and restraint configurations were examined, including standard 3-point belt only, force-limited 3-point belt, force-limited 3-point belt plus pretensioner, and 3-point belt plus airbag. While specific PMHS anthropometric selection criteria varied between these test series, subjects are pre-screened for pre-existing skeletal conditions (e.g. cervical spine fractures, and/or severe degenerative changes).

III. RESULTS

The correlation matrices are presented for the primary cervical spine and craniovertebral ligaments. In the correlation matrices, red color indicates positive correlation and blue color indicates negative correlation. Correlation coefficients were graded as follows: Strong: 0.8 – 1.0, Good: 0.7 – 0.8, Reasonable: 0.6 – 0.7, Weak: 0.5 – 0.6, Poor: 0.3 – 0.5 and No/Very poor: 0.0 - 0.3. Fig. 7 shows the results for primary cervical spine ligaments. These results are broken down based on the type of ligament (ALL, PLL etc.).

	C7T1ALL	C6C7ALL	C5C6ALL	C4C5ALL	C3C4ALL	C2C3ALL
Axial_Force	-0.32	-0.48	-0.44	-0.42	-0.07	-0.09
Moment	0.55	0.36	0.41	0.42	0.70	0.64

(a)

	C7T1PLL	C6C7PLL	C5C6PLL	C4C5PLL	C3C4PLL	C2C3PLL
Axial_Force	0.76	0.85	0.91	0.91	0.93	0.95
Moment	-0.03	0.18	0.55	0.84	0.79	0.63

(b)

	C7T1ISL	C6C7ISL	C5C6ISL	C4C5ISL	C3C4ISL	C2C3ISL	C1C2ISL
Axial_Force	0.69	0.68	0.67	0.69	0.73	0.71	0.10
Moment	-0.12	-0.13	-0.13	-0.12	-0.02	-0.08	0.81

(c)

	C7T1LF	C6C7LF	C5C6LF	C4C5LF	C3C4LF	C2C3LF
Axial_Force	0.70	0.70	0.70	0.71	0.78	0.77
Moment	-0.10	-0.11	-0.10	-0.10	0.07	0.04

(d)

	C7T1CL	C6C7CL	C5C6CL	C4C5CL	C3C4CL	C2C3CL	C1C2CL	OCC1CL
Axial_Force	0.80	0.91	0.82	0.83	0.83	0.65	0.86	-0.19
Moment	0.07	0.69	0.16	0.22	0.21	0.90	0.77	0.58

(e)

Fig. 7. Correlation matrix for: a) Anterior longitudinal ligaments (ALL); b) Posterior longitudinal ligaments (PLL); c) Interspinous ligaments (ISL); d) Ligamentum Flavum (LF); and e) Capsular ligaments (CL).

For the primary cervical spine ligaments, the strain in ligamentum flavum (LF) at all spinal levels had a good correlation with OC axial force but had no correlation with the OC moment (Fig. 7(d)). The strain in posterior longitudinal ligaments (PLL) had good to strong correlation with OC axial force at all spinal levels but had good to strong correlation with OC moment only at the C3-C4 and C4-C5 levels (Fig. 7(b)). Strain in interspinous ligaments (ISL) had a reasonable to good correlation with the OC axial force at all spinal levels except at C1-C2 level. At this level, the ISL had strong correlation with the OC moment (Fig. 7(c)). At most of the cervical spinal levels, strain in the capsular ligaments (CL) had strong correlation with OC axial force except at C2-C3 level which showed strong correlation with OC moment (Fig. 7(e)). The strain in the capsular ligament between the OC and C1 showed weak correlation with OC moment and no correlation with OC axial force (Fig. 7(e)). Unlike other primary ligaments, the strain in anterior longitudinal ligaments (ALL) had poor to no correlation with OC axial force (Fig. 7(a)). Also at most levels, the strain in ALL did not show a good correlation with OC moment, with the exception of reasonable correlation at C2-C3 level and good correlation at C3-C4 level (Fig. 7(a)).

For the craniovertebral ligaments (Fig. 8), the strains in the anterior atlanto-axial ligaments and in the anterior atlanto-occipital ligaments, which are a continuation of the anterior longitudinal ligament (ALL), showed stronger correlation with OC moment compared to OC axial force (Fig. 8(a)). The strains in the posterior atlanto-axial ligaments and the posterior atlanto-occipital ligaments also showed reasonable to strong correlation with OC moment but no correlation with OC axial force (Fig. 8(a)). For the cruciate ligaments (UPPER_CRUX and LOWER_CRUX), OC axial force showed good to strong correlation with strains, but OC moment had no correlation with strains (Fig. 8(c)). The transverse ligament strain did not show a strong correlation with either the OC force or the OC moment (Fig. 8(c)). Both the tectorial (Fig. 8(c)) and apical (Fig. 8(b)) ligaments showed strong correlation with OC axial force. The strain in the alar ligament connecting the dens to the atlas showed weak correlation with the OC axial force and no correlation with the OC moment, but the strain in alar ligament connecting dens to the skull showed a strong correlation with OC moment (Fig. 8(b)). For flexion simulations, strains were higher in the alar ligament connecting the dens to the atlas and for extension simulations, strains were higher in the alar ligament connecting the dens to the skull. It was found that with all alar ligaments combined, OC moment was a better predictor of strain than OC force (MAX_ALAR in Fig. 8(b)).

	AA_AM	AA_OM	PA_AM	PA_OM
Axial_Force	0.79	0.69	0.22	-0.21
Moment	0.93	0.81	0.87	0.60

(a)

	DENS_SKULL_ALAR	DENS_ATLAS_ALAR	DENS_SKULL_APICAL	MAX_ALAR
Axial_Force	0.15	0.55	0.87	0.27
Moment	0.83	-0.21	0.41	0.76

(b)

	TRANSVERSE	TECTORIAL	UPPER_CRUX	LOWER_CRUX
Axial_Force	0.56	0.82	0.71	0.86
Moment	-0.24	0.23	-0.06	0.17

(c)

Fig. 8. Correlation matrix for: a) Anterior and posterior atlanto-axial and atlanto-occipital ligaments; b) Dens ligaments; and c) Transverse, Tectorial and cruciate ligaments.

For occiput (flexion) and forehead (extension) impacts, the ligaments where high strains frequently occurred were identified and are shown in Table III.

TABLE III.
LIGAMENTS WITH HIGHEST STRAINS

Impact Type	Highest strain	Second highest strain	Third highest strain
Flexion	Dens-atlas alar; ISL @C6-C7	ISL @C6-C7; CL@C6-C7	CL@C6-C7; Dens-atlas alar; CL@C7-T1
Extension	CL@OC-C1	Dens- skull alar; CL@C6-C7	Dens-skull alar; CL@C6-C7

***ISL=interspinous ligament; CL=capsular ligament**

CIREN and PMHS data analysis

From the CIREN database, 92 occupants (front row, belted and airbag restrained) who sustained one or more AIS 2+ cervical spine injuries in frontal crashes were identified from case years 2005-2015. Although only frontal collisions were considered, the cervical spine injuries sustained were caused by a variety of different mechanisms including all four primary loading modes (flexion, extension, tension, compression), as well as combined loading (e.g. Compression/Flexion). In addition, the most commonly involved physical components were the belt (flexion/extension of the neck due to restraint of the torso by the belt), A-pillar (head contact), steering wheel (head contact), and airbag (head/torso restraint by the airbag). Of the 92 cases, 12 were associated with documented ligamentous injury (Table IV). In several other cases, ligamentous injury was "suspected" but unconfirmed. For the entire subset of cervical spine injuries, 50% (n=46) were to the lower spine (C4-C7), 41% (n=38) were to the upper spine (C1-C3) and 9% (n=7) had both upper and lower c-spine injuries. Of the 12 cases with ligamentous injuries, seven were exclusively in the lower spine, four were in the upper spine and one case had ligamentous damage encompassing both upper and lower c-spine.

TABLE IV
LIGAMENTOUS CERVICAL SPINE INJURIES THAT WERE SUSTAINED CONCOMITANTLY WITH AIS 2+ CERVICAL SPINE INJURY IN FRONTAL CRASHES IN BELT AND AIRBAG RESTRAINED FRONT ROW OCCUPANTS OF THE CIREN DATABASE.

CIRENID	Ligaments* Injured
100112061	ISL@C4-C5
160131684	ALL, PLL, ISL @C4-C5
352173925	ALL, PLL@C2
357135746	ISL@C2
385134546	LF, PLL, ALL@C6-C7
431870476	PLL, ISL disruption @C2-C6; ALL, LF@C5-C7
588547709	LF@C6-C7
588557622	LF@C7
588588658	ALL@C6-C7
588623159	ALL@C4-C5
588817897	ALL@C2
588819950	PLL@C2 with injury to the posterior atlanto-occipital membrane

*ISL=interspinous ligament; LF=ligamentum flavum; ALL=anterior longitudinal ligament; PLL=posterior longitudinal ligament

Eleven AIS 2+ cervical spine injuries were identified from five different PMHS sled test series. Of those, nine had associated ligamentous damage, all of which occurred in the lower spine (C4-C7). The ligaments damaged in these frontal sled tests were: interspinous ligament (n=6), supraspinous ligament (n=5), ligamentum flavum (n=6), anterior longitudinal ligament (n=5), intertransverse ligament (n=2), posterior longitudinal ligament (n=2), and capsular ligament (n=2) (Table V). Although the test series were focused on frontal impacts, and therefore the predominant mechanism was flexion, interaction with the airbag in two tests resulted in "extension" type injuries.

TABLE V
LIGAMENTOUS CERVICAL SPINE INJURIES SUSTAINED IN PMHS IN FRONTAL SLED TESTS

NHTSA Database#	C-spine injury	Ligaments* Injured	Restraint*Condition
11509	C7-T1 bilateral facet dislocation	ISL, SSL, LF, PLL@C7-T1	3-point FB
11510	C7-T1 disruption, C7 body FX	ISL, SSL, LF@C7-T1	3-point FB
[27]	C4 anterior body FX	ALL @C4	3-point SB
9337 [28]	C6-C7 unilateral facet dislocation	ISL, LF, CL@C6-C7	3-point SB
9338 [28]	Complete C4-C5 transection	ALL, CL, ISL, SSL, PLL, ITL, LF@C4-C5	3-point SB
9339 [28]	C7-T1 bilateral facet dislocation	SSL, ISL, LF, ITL@ C7-T1	3-point SB
11500	C5-C6, C6-C7 disc injuries	ALL@C5-C7	3-point FB with airbag
11501	C6-C7 disc disruption	ALL@C6-C7	3-point FB with airbag
11518	C6-C7 facet joint disruption	ISL, SSL, LF@C6-C7	3-point FB

*ISL=interspinous ligament; SSL=supraspinous ligament; LF=ligamentum flavum; ALL=anterior longitudinal ligament; PLL=posterior longitudinal ligament; ITL=intertransverse ligament; CL=capsular ligament; SB=standard belt; FB=force-limited belt; FX=fracture

IV. DISCUSSION

The main purpose of this study was to analyze the correlation of both the axial force and the moment at the OC with strain in the various cervical spine ligaments to test our hypothesis that both OC axial force and moment are necessary to predict neck injuries. This study was conducted to identify the importance of using both force and moment in the neck injury criteria (Nij) that is used for neck injury assessment, as specified in Federal Motor Vehicle Safety Standards (FMVSS). Biomechanical research experiments conducted with volunteer humans, porcine subjects and PMHS suggested the inclusion of both axial force and bending moment of the neck for a general tolerance criterion for cervical spine injury [29-34] and this was the basis for the development of the Nij criterion in use today. Similarly, our study also demonstrated the importance of both axial force and moment but using a computational approach.

In this computational study, because of longer runtime of the GHBMC M50-O model (~25hrs on 128 processors for a 120ms event), the frontal/rear end collisions were simulated as head impacts with a linear impactor to produce sagittal head neck motion. Though the impact severity may not be similar when simulating full scale crash as a head impact but it does generate similar head-neck motion as seen in frontal/rear end collisions which can help analyze the strain generated in the ligaments and investigate their correlation with kinematic parameters.

The material formulation (*MAT 074) in LS-DYNA [17] uses three load curves to define the non-linear force-displacement response of the beam elements forming the cervical spine ligaments in the GHBMC model. Since different ligaments can engage at different times during the loading cycle and are defined with different material properties (load curves) in the GHBMC model, the maximum strain measured for the different ligaments can occur at different times. The ligaments will only fail when they reach their strain threshold. Thus, regardless of the timing of maximum strain, it is worthwhile to examine the kinematic parameters that correlate with maximum strain in the various ligaments and consequently can be used in formulation of an injury metric for predicting injuries.

Simulation results from our study showed that the axial force at the OC correlated well with the strain in most of the ligaments. For primary cervical spine ligaments, OC axial force showed reasonable to strong correlation with strain in most of the ligaments except ALL whereas OC moment showed reasonable to strong correlation with strain in only a few ligaments at certain spinal levels. The reasonable to strong correlation of the OC axial force with strain in most primary ligaments at various cervical spinal levels demonstrates its good injury predictive capability for both upper and lower neck injuries. While Nij (which is calculated at the upper neck) has not been validated for use with lower neck injuries, these results suggest that it may be applicable for all neck injuries and not just upper neck injuries. In contrast to the primary cervical spine ligaments, where axial force was the predominant factor, analysis of the craniovertebral ligaments demonstrated OC moment to be equally important.

CIREN and PMHS data showed that in impact conditions similar to those simulated in this study, the ligamentous injuries can encompass a range of primary cervical spine ligaments, namely anterior longitudinal ligaments, posterior longitudinal ligaments, interspinous ligaments, ligamentum flavum and capsular ligaments, as well as craniovertebral ligaments connected to the dens. Most ligamentous injuries documented in the CIREN and PMHS datasets were at the lower c-spine level, which is where the high strains were seen in the flexion simulations (Table III). Of all the flexion simulations, 70% had highest strain at the C6-C7 level in the ISL ligament while 30% had highest strain in the dens-atlas alar ligament. The CIREN and PMHS data are limited by the small total number of injuries evaluated and, given the nature of these convenience samples, the results are not necessarily representative of the entire population of automotive injuries. Nonetheless, these findings help to put the results of the parametric study in context by demonstrating ligamentous injuries in real world and simulated crashes.

If injuries in the field were limited to lower c-spine and primary cervical spine ligaments, OC axial force could be considered sufficient to predict injuries, as OC axial force showed better correlation with strains in the various primary ligaments at the lower c-spine levels. However, three cases from the CIREN database had ligamentous injury at the dens and one had injury at the PA-OM. Simulations also showed high strains in the dens alar ligaments for both flexion and extension (Table III). Other research studies have also indicated the vulnerability of the alar ligaments to damage in motor vehicle crashes [35-39]. Strain in the alar ligament show good to strong correlation with OC moment. Apart from the craniovertebral ligaments, there were also a few primary ligaments that showed better correlation with OC moment than axial force. Thus, OC moment could not be eliminated as a predictor for ligamentous neck injuries.

The GHBMC neck model is well validated. Specifically, the cervical spine ligaments which are the focus of this study have been validated using the strain results obtained from in-vitro cervical spine studies during an 8g frontal impact and 8g rear impact [15] [40]. The head impacts simulated in this paper are similar to the validation tests and also the GHBMC model has a high score for crash induced injury (CII) prediction of ligamentous injuries [41], which gives confidence in the results of this study.

This study has certain limitations. First, only ligamentous cervical spine injuries were analyzed and as a result the importance of axial force and moment at OC cannot be extrapolated to other neck injuries based on this study. Second, it is limited by the small number of simulations. The correlations can change if more data points are added to the design space or if the variable range is expanded. The correlation could also be affected by adding more variables, such as muscle activation and ligament laxity, which were not considered in this study. The GHBMC model in a driving position with normal lordotic curvature of the spine was considered in this study. Different seating postures might affect the curvature and thus the correlations [42]. A change in correlations could have an effect on the importance of axial force and moment in predicting neck injuries. Finally, the GHBMC human model used for this study represents a particular human. Although the correlation results cannot be extrapolated to the entire population due to human variability, the use of numerical models can help identify important kinematic parameters to be considered for injury prediction. In addition, the simulation findings were supported by field data demonstrating ligaments commonly injured in real automotive crashes.

V. CONCLUSIONS

The field data analysis and simulation based correlation results support our hypothesis that the combined knowledge of the axial force and the moment at the OC are required for predicting both the primary and craniovertebral ligamentous cervical spine injuries.

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