MORPHOLOGICAL INEQUITIES? NUMERICAL SIMULATION OF CERVICAL SPINE INJURIES IN RUGBY.

Alexandra Lanièce[1] & David Brauge[2], Aurélien Laville[1], Wafa Skalli[1] & Sébastien Laporte[1]
Institut de Biomécanique Humaine Georges Charpak, Paris, France[1]
Pôle Neuroscience-Neurochirurgie, Hôpital de Purpan, Toulouse, France[2]

The purpose of this study was to identify cervical spine morphologies at risk in rugby games. A parameterized osteoarticular finite element model of the cervical spine modeled 17 subjects under three different loadings, each being representative of rugby game phases: scrum (unconstrained axial compression), tackle (full-constraint axial compression) and collapsing scrum (hyperflexion). Stress and strain in the spine were recorded to determine appearances of injuries. The comparison of these injuries with the literature validated the model for injury prediction. A correlation analysis linked parameters of the morphology with the injury prediction and key parameters such as articular facet orientation arose. Precisely identifying all these parameters could help designing preventive clinical guidelines for rugby players.

KEY WORDS: finite element model, parameterized, hyperflexion, screening.

INTRODUCTION: Neck injuries are critical in contact sports. For rugby players, 33.3% (Stephenson, 1996) of injuries are sustained in the neck region. These traumatic injuries result in vertebral fractures, articular facet dislocations and soft tissue damage (ligament tear or intervertebral disk disruption) (Cusick & Yoganandan, 2002). To limit these incidents, the French Rugby Federation implemented compulsory preventive screening based on medical and radiological examinations of rugby players. However the exclusion criteria that were provided are widely debated, as they are only based on experts' opinion, without scientific demonstration. Our interest is the mechanical behavior of the cervical spine that leads to these injuries.

Many studies (Clausen, 1997; Maurel, 1997; Fréchède, 2006; Laville, 2009) highlighted the influence of some geometrical parameters on the motion of the spine. However there is no extensive study correlating the morphology and the mechanical behavior. The purpose of this work is to establish guidelines for the preventive clinical examination of rugby players. This means determining the geometrical parameters of the spine that play a preponderant role in injury mechanism. We focus on three rugby-like impacts: scrum, tackle and hyperflexion. To this day, only the scrum mechanism has been precisely quantified (Preatoni, 2013 & 2015; Cazzola, 2015).

METHODS: A numerical model was used to observe the failure mechanisms of the cervical spine and to compare different morphologies (see Figure 1). The morphologies of 17 subjects were obtained from bi-planar X-rays, and a semi-automated method extracted all the geometrical parameters describing the cervical spine. Then these parameters were inserted in the subject-specific model developed by Laville (2009), generating a cohort of numerical patients.

The numerical model was meshed via homemade MatLab routines and represents the cervical spine from C0 to T1. The intervertebral disks and the ligaments (anterior longitudinal, posterior longitudinal, flavum, interspinous, posterior and anterior capsular ligaments) were modeled by tension-only springs, and the bones with rigid bodies. In this study, the muscles were voluntarily left out; accounting for this, the weight of the head was removed. The model comprises 11920 nodes for a total of 8510 elements. All the patients were implemented the same material properties so that their mechanical behavior depended only on their geometry.

Three different injury mechanisms were chosen to apply on our numerical cohort. Each mechanism was representative of rugby game phases: scrums (unconstrained axial compression), tackles (full constraint axial compression) and collapsing scrums (hyperflexion). The precise boundary conditions were chosen to match cadaver experiments from the literature, to be confronted to the model. The axial compression cadaver data were obtained from Nightingale (1991) and the hyperflexion data from Pintar (1998). All loadings were implemented at the center of the occipital condyles, with the lower end plate of T1 fixed. All simulations were loaded up to failure. These loading were all axial compressions, at 0.01m/s for tackle, 0.045 m/s for scrum and 3m/s for hyperflexion. Only for tackle was the rotation of the skull blocked.

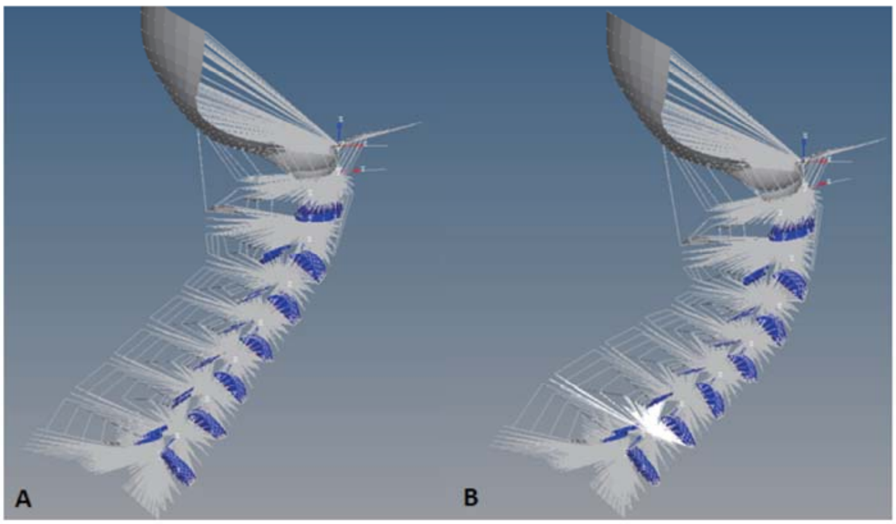

Figure 1: Finite element model before (A) and after (B) tackle simulation.

The explicit solver used for the simulations was Radioss (Altair Engineering, Troy, USA). For each simulation, the linear strain in the ligaments, the local stress in the vertebrae and the global stress in the spine were recorded. Mechanical parameters were confronted to injury criteria gathered from the literature (Pintar 1989 & 1995; Yoganandan, 1996 & 2001) to establish the chronological appearance of injuries during the simulations.

The mechanical output of the finite element solver was harvested in MatLab. A Spearman correlation study was ran between these parameters and the geometrical parameters describing the cervical spine. Parameters were considered correlated if they had a correlation coefficient above 75% and a p-value below 0.001.

RESULTS and DISCUSSION: Two types of results were extracted from these simulations. Firstly, the mechanical response was compared to the literature to validate the model in motion and injury prediction. Secondly the correlation study underlined the morphological parameters that influence the output of the simulations. The first two injuries occurring during the simulations are recapitulated in Table 1.

Model validation: Tackle first injuries can be explained as the result of the stress concentration occurring at C7 level. Both tackle and scrum results were coherent with the cadaver injuries reported by Nightingale (1991). Hyperflexion mechanism induced traction and posterior damages, due to the global buckling of the spine. Similar injuries were described by Pintar (1998) in his cadaver study. According to the recent work of Awad (2015), observing ligamentous rupture and bone damage at different levels is indeed frequent in traumatic cervical spine injuries. The coherence of the model with the literature data indicates that this model is valid for injury prediction regarding the type and the location along the spine.

Table 1
Injuries recorded for each rugby game phase

Simulation type	First injuries	Secondary injuries
Tackle	- Interspinous ruptures at C7-T1	- Compression/Traction fractures at C4-C6 - Posterior ligament ruptures
Scrum	- Interspinous ruptures between C2 and T1	- Interspinous ruptures between C2 and T1 - Traction fractures at C4
Hyperflexion	- Interspinous ruptures at C2-C3	- Traction fractures at C4 and C6 - Posterior ligament ruptures between C5 and T1

Correlation study: The correlated couples are listed in Table 2. Correlated parameters can be sorted into three different categories: articular facet orientation, vertebral end plate size and orientation, and neck curvature. The influence of each of these parameters were perceived in previous studies (Maurel, 1997; Fréchède, 2006), but were never quantified. In particular, the importance of vertebral end plate size is associated to the load it carries during impact. This correlation could explain a phenomenon frequently observed by clinicians: cervical platyspondyly. Indeed, rugby players often present a progressive enlargement of their vertebrae during their career (Torg, 1993).

Table 2
Correlated parameters with a p-value below 0.001

Mechanical parameter	Deflection - Hyperflexion	Neck rigidity - Scrum	Neck rigidity - Scrum	Time of rupture - Tackle	Flexion moment - Tackle	Flexion moment - Tackle	Neck rigidity - Tackle
Geometrical parameter	C3 facet sagittal orientation	C5 facet transversal orientation	C5 facet sagittal orientation	C6 inferior end plate orientation	C6 inferior end plate orientation	C3 width (vertebral body)	Neck lordosis

CONCLUSION: A parameterized finite element model of the cervical spine was validated for injury prediction. This work underlined the influence of the morphology on the global mechanical behavior of the spine. This influence was quantified for the first time, and not only qualified. With the participation of more subjects to enrich the statistics, this method will allow determining threshold values of morphological parameters to avoid neck injuries in sports. Clinicians will be able to measure these parameters on X-rays during the preventive examination of athletes.
This work is a proof of concept of the method, and will be supplemented with numerous subjects, and a muscular analysis too.

REFERENCES:

Cazzola, D., Preatoni, E., Stokes, K. A., England, M. E., & Trewartha, G. (2014). A modified prebind engagement process reduces biomechanical loading on front row players during scrummaging: a cross-sectional study of 11 elite teams. *British journal of sports medicine*, bjsports-2013 -092904.

Clausen, J. D., Goel, V. K., Traynelis, V. C., & Scifert, J. (1997). Uncinate processes and Luschka joints influence the biomechanics of the cervical spine: Quantification using a finite element model of the C5-C6 segment. *Journal of Orthopaedic Research*, *15*(3), 342-347.

Cusick, J. F., & Yoganandan, N. (2002). Biomechanics of the cervical spine 4: major injuries. *Clinical Biomechanics*, *17*(1), 1-20.

Frechede, B., Bertholon, N., Saillant, G., Lavaste, F., & Skalli, W. (2006). Finite element model of the human neck during omni-directional impacts. Part II: relation between cervical curvature and risk of injury. *Computer methods in biomechanics and biomedical engineering*, *9*(6), 379-386.

Laville, A., Laporte, S., & Skalli, W. (2009). Parametric and subject-specific finite element modelling of the lower cervical spine. Influence of geometrical parameters on the motion patterns. *Journal of biomechanics*, *42*(10), 1409-1415.

Nightingale, R. W., Myers, B. S., McElhaney, J. H., Richardson, W. J., & Doherty, B. J. (1991). The influence of end condition on human cervical spine injury mechanisms. *SAE paper*, (912915).

Maurel, N., Lavaste, F., & Skalli, W. (1997). A three-dimensional parameterized finite element model of the lower cervical spine, study of the influence of the posterior articular facets. *Journal of biomechanics*, *30*(9), 921-931.

Pintar, F. A., Yoganandan, N., Sances, A., Reinartz, J., Harris, G., & Larson, S. J. (1989). Kinematic and anatomical analysis of the human cervical spinal column under axial loading. *SAE Technical Paper,* (No. 892436).

Pintar, F. A., Yoganandan, N. A., Voo, L., Cusick, J. F., Maiman, D. J., & Sances, A. (1995). Dynamic characteristics of the human cervical spine. In *Proceedings: Stapp Car Crash Conference* (Vol. 39, pp. 195-202). Society of Automotive Engineers SAE.

Pintar, F. A., Voo, L. M., Yoganandan, N. A., Cho, T. H., & Maiman, D. J. (1998). Mechanisms of hyperflexion cervical spine injury. In *Proceedings of the International Research Council on the Biomechanics of Injury conference* (Vol. 26, pp. 249-260). International Research Council on Biomechanics of Injury.

Preatoni, E., Stokes, K. A., England, M. E., & Trewartha, G. (2013). The influence of playing level on the biomechanical demands experienced by rugby union forwards during machine scrummaging. *Scandinavian journal of medicine & science in sports*, *23*(3), e178-e184.

Preatoni, E., Stokes, K. A., England, M. E., & Trewartha, G. (2015). Engagement techniques and playing level impact the biomechanical demands on rugby forwards during machine-based scrummaging. *British journal of sports medicine*, *49*(8), 520-528.

Stephenson, S., Gissane, C., & Jennings, D. (1996). Injury in rugby league: a four year prospective survey. *British journal of sports medicine*, *30*(4), 331-334.

Torg, J. S., Sennett, B., Pavlov, H., Leventhal, M. R., & Glasgow, S. G. (1993). Spear tackler's spine An entity precluding participation in tackle football and collision activities that expose the cervical spine to axial energy inputs. *The American journal of sports medicine*, *21*(5), 640-649.

Yoganandan, N., Kumaresan, S., Voo, L., & Pintar, F. A. (1996). Finite element applications in human cervical spine modeling. *Spine*, *21*(15), 1824-1834.

Yoganandan, N., Kumaresan, S., & Pintar, F. A. (2001). Biomechanics of the cervical spine Part 2. Cervical spine soft tissue responses and biomechanical modeling. *Clinical biomechanics*, *16*(1), 1-27.

Acknowledgement

The authors would like to thank the Fédération Française de Rugby for their support.