Changes of the Cervical Spine in Response to Head-first Impact in Rugby:
A Finite Element Analysis

YOSHINORI HASEGAWA*1), TAKAYUKI KAWASAKI*1), YUSUKE MIYAZAKI*2), SHOGO SOBUE*1),
TAKEFUMI KAKETA*1), YOSHINORI GONDA*1), KAZUO KANEKO*1)

*1) Department of Orthopaedic Surgery, Juntendo University Faculty of Medicine, Tokyo, Japan,
*2) Department of Systems and Control Engineering, Tokyo Institute of Technology, Tokyo, Japan

Objectives: To examine the effects of (1) trunk constraint and (2) the entry angle on the cervical spine in response to a head-first impact.

Materials: The AM50 Total HUmanModel for Safety (THUMS®) v4.02, pedestrian finite element model, was subjected to head-first impacts.

Methods: The impact speed was 3.2 m/s. The following patterns were simulated: entry angle (0°, 15° to the sagittal plane) and trunk constraint (constraint, unconstraint).

Results: As a result of head-first impact, the upper cervical spine was extended and the lower cervical spine was markedly flexed when the trunk was constrained. The mean stress applied to the cervical spine was significantly increased when the trunk was constrained, as indicated by the Mann–Whitney U test.

Conclusions: In a head-first impact, the mean stress on the cervical spine increases significantly when the trunk is constrained. In order to reduce the risk of cervical spine injuries, it is desirable not to bind with teammates before a head-first impact.

Key words: rugby, head-first impact, cervical spine injury, finite element methods

Introduction

In rugby, players are exposed to a possible risk of head and neck injury during competition1). The cause of catastrophic head and neck injury includes several factors, such as misjudgment, improper posture, and education about collision. In the past, the scrum is the most frequent mechanism of these injuries because its collapse directly leads to the head hitting the ground, and binding with teammates further increases the impact force. To decrease damage to the head and neck, the World Rugby revised the scrum regulations in 2013 (https://rugbyreferee.net/2013/05/08/breaking-news-new-scrum-engagement-process-approved-for-glob al-trial-rugbyref-scrum-rugbyunited/). The point of the revised scrum process is that props, front row players, use their outside arm to grip the opponent players before engagement. These scrum law variations contributed to a decrease in severe injury6). These changes have improved the safety of rugby competitions. However, there are still some mechanisms that may cause severe injuries that have not yet been discussed.

Rucks and mauls are crowded situations where players are competing for the ball. Unlike set plays such as scrums, they occur in post-tackle sequences and there are many variations in the collisions. Ball contest in such situations, the so-called “breakdown”, is one of the alternative mechanisms of head
and neck trauma. Breakdowns are the third most frequent cause of severe injuries, after tackles and scrums\textsuperscript{6-8}). Players usually collide with their opponents from the head or shoulder, and they may also bind with teammates just before an impact. These actions are considered high risks for head and neck injuries. Previous studies have reported that trunk constraint and preflexion affect the cervical load and cervical momentum\textsuperscript{9}, but none have investigated the stresses at the sites in detail, at the point of collisions. Therefore, the aim of the present study was to examine the stress placed upon the cervical spine by the effects of (1) trunk constraint, and (2) the entry angle of impact. We investigated these issues by using the finite element method (FEM). We hypothesized that trunk constraint and entry angle of impact affected head-first impacts. Findings from this study may contribute to the safety of rugby players.

Materials and Methods

The AM50 Total HUman Model for Safety (THUMS\textsuperscript{®}) v4.02 (Toyota Central R&D Labs., Inc. Aichi, Japan), pedestrian finite element model, was subjected to head-first impacts at selected direction and trunk constraint. The THUMS cervical spine has previously been validated against multiple cadaver tests\textsuperscript{10-13}. Impact conditions were set using Hyper-Mesh and Hyper-Crash (Altair Engineering Inc. Michigan, USA). All simulations were performed with LS-DYNA nonlinear explicit finite element solver version 971 (Livermore Software Technology Corporation. California, USA) in Supercomputer Tsubame 3.0 (Tokyo Institute of Technology. Tokyo, Japan). Post-processing was carried out using LS-PrePost-4.3 (Livermore Software Technology Corporation. California, USA).

1. Impact condition settings

The impact speed was 3.2 m/s with reference to a previous report\textsuperscript{14}. The following four patterns were used for the entry angle and trunk constraint.

1. entry angle 0°, trunk constraint (0+)
2. entry angle 0°, no trunk constraint (0−)
3. entry angle 15°, trunk constraint (15+)
4. entry angle 15°, no trunk constraint (15−)

2. Data collection

We adopted C1 as the upper cervical spine, C4 as the middle cervical spine, and C7 as the lower cervical spine. C1 was divided into 2 parts (anterior column and posterior column). C4 and C7 were divided into 3 parts (anterior, middle, and posterior columns) (Figure-1).

For each pattern, 20 elements were randomly selected, and the mean stress was calculated. For the above four simulation patterns, the mean stress of each column was recorded every 5 ms, up to 35 ms.

We also measured the OC2 angle for the upper cervical angle, C2C7 angle for the middle cervical angle, and C6Th1 angle for the lower cervical angle (Figure-2). Each angle was recorded every 5 ms, up to 30 ms.

3. Statistical analysis

The outcome measure was the mean stress of each column in C1, C4, and C7. Comparisons of the outcome measurement described as earlier among
the tasks were analyzed using the Mann–Whitney U test with 2 × 2 factors: entry angle (0°, 15° of sagittal plane) and condition of the trunk constraint (constraint, unconstraint). P value of < 0.05 was considered statistically significant. All tests were two-sided. The data analyses were conducted using R for Windows v. 3.5.2 (The R Project).

Results

In this study, the effects of the entry angle of impact and trunk constraint on the cervical spine was measured using FEM. Regarding the alignment of the cervical spine at the time of collision, the upper cervical spine was extended and the lower cervical spine was markedly flexed when the trunk was constrained. When the trunk was not constraint, the upper cervical spine was also extended, but the lower cervical spine showed normal to mild flexion, and the middle cervical spine was markedly extended (Figures-3, 4).

The maximum stress and site for each condition were as follows: 250 MPa at anterior column of C7 with entry angle 0° and trunk constraint; 87 MPa at posterior column of C4 with entry angle 0° and no trunk constraint; 239 MPa at anterior column of C7 with entry angle 15° and trunk constraint; and 67 MPa at posterior column of C4 with entry angle 15° and no trunk constraint (Figure-5).

The stress applied to the cervical spine was significantly increased with trunk constraint as indicated by the Mann–Whitney U test. In contrast, there was no significant increase in stress with the tested entry angles of impact.

Discussion

In this study, the influence of the entry angle of impact and trunk constraint on the cervical spine was measured using the finite element method. In general, the stresses occurring in the cervical spine were significantly greater when the trunk was constrained, but there was no significant difference in cervical spine stress at the tested angles of impact. The site and magnitude of the maximum stress was approximately 250 MPa in the anterior column of C7 with trunk constraint, and about 70 MPa in the posterior column of C4 without trunk constraint. Both the site of onset and magnitude of

![Figure-3](image-url)  
**Figure-3** A: head–first impact after 35 ms with entry angle 0° with trunk constraint, B: head–first impact after 35 ms with entry angle 0° without trunk constraint

![Figure-4](image-url)  
**Figure-4** Changes in cervical spine angle at 30 ms
0+: entry angle 0° with trunk constraint
0−: entry angle 0° without trunk constraint
15+: entry angle 15° with trunk constraint
15−: entry angle 15° without trunk constraint
stress were significantly different in the presence and absence of trunk constraints.

Comparing the results of the previous cadaver experiment\(^\text{15}\) and the trunk constraint of the current study, the cervical posture (extension in the upper cervical spine and flexion in the lower cervical spine) and the site of fracture (C7) were similar (Figure 3). In the cadaveric experiment, the cervical spine of the corpse was rigidly fixed to the mass as the trunk, simulating the constrained trunk. We also considered trunk constraint in this simulation to reproduce the results of the cadaveric experiment. When the trunk was constrained, the stress was significantly increased in the entire cervical spine. This suggests that trunk constraint may be a significant risk factor for cervical spine injuries. In actual play, binding with teammates is considered a trunk constraint and should be avoided before a head-first impact.

We hypothesized that the head down position would also significantly increase stress on the cervical spine, but the results did not demonstrate this. A previous FEM study\(^\text{9}\) showed a significant increase in load and momentum with cervical flexion, but the current simulation may be influenced by the fact that the simulation was tested with the head down but without cervical flexion, meaning without cervical spine straightening. The reason why the head down position is said to be dangerous is not the head position in itself, but the straightening of the cervical spine due to cervical flexion. If that is so, players with a straight neck...
may be at greater risk for cervical spine injuries, even if they do not flex their cervical spine.

Actual cervical spine injuries in rugby are reported to occur mainly in the posterior part of the middle cervical spine (C4 and C5), and fracture and dislocation are common. In the present simulation, the maximum stress was generated at the posterior column of C4, and the middle cervical spine was markedly extended when the trunk was not constrained, suggesting that the actual cervical spine injury may have occurred without trunk constraint. As mentioned above, the cadaveric experiment was performed with trunk constraint; and the FEM is useful for simulations without a trunk constraint, which may enable a more realistic simulation to be performed.

The present study had some limitations. Although the model was a general male individual, there are individual differences in the arrangement and posture of the cervical spine, and it is unknown whether these results can be generalized. Also, this experiment does not consider the effect of muscle tone. Naturally, changes in stress and cervical spinal alignment may change with muscle tension, so it is unclear whether it accurately approximates the collision situation in rugby competitions. In addition, the trunk was constrained at Th1 in this study, but it is not clear whether binding occurs at Th1 during a scrum or breakdown in rugby in reality. Moreover, although the entry angle in this study was based on the sagittal plane only, it is necessary to consider the three-dimensional angle including the coronal plane in actual collisions. Further simulations under detailed conditions, are required.

Conclusion

In a head-first impact, the mean stress on the cervical spine increases significantly when the trunk is constrained. In order to reduce the risk of injury to the cervical spine, it is desirable to avoid binding with teammates prior to a head-first impact.

Acknowledgment

The authors thank Shoya Awamori for supporting the present study.

References

1) Fuller CW, Brooks JHM, Cancea RJ, Hall J, Kemp SP: Contact events in rugby union and their propensity to cause injury. Br J Sports Med, 2007; 41: 862–867; discussion 867.
2) Roberts SP, Trewartha G, England M, Stokes KA: Collapsed scrums and collision tackles: what is the injury risk? Br J Sports Med, 2015; 49: 536–540.
3) Quarrie KL, Cantu RC, Chalmers DJ: Rugby union injuries to the cervical spine and spinal cord. Sports Med, 2002; 32: 633–633.
4) Cazzola D, Pretoni E, Stokes KA, England ME, Trewartha G: A modified prebind engagement process reduces biomechanical loading on front row players during scrumming: a cross-sectional study of 11 elite teams. Br J Sports Med, 2015; 49: 541–546.
5) Trewartha G, Pretoni E, England ME, Stokes KA: Injury and biomechanical perspectives on the rugby scrum: a review of the literature. Br J Sports Med, 2015; 49: 425–433.
6) Berry JG, Harrison JE, Yeo JD, Cripps RA, Stephenson SCR: Cervical spinal cord injury in rugby union and rugby league: are incidence rates declining in NSW? Aust N Z J Public Health, 2006; 30: 268–274.
7) Brown JC, Lambert MI, Verhagen E, Readhead C, van Mechelen W, Viljoen W: The incidence of rugby-related catastrophic injuries (including cardiac events) in South Africa from 2008 to 2011: a cohort study. BMJ Open, 2013; 3: e002475.
8) Carmody DJ, Taylor TKF, Parker DA, Coolican MRJ, Cumming RG: Spinal cord injuries in Australian footballers 1997–2002. Med J Aust, 2005; 182: 561–564.
9) Nightingale RW, Sganga J, Cutcliffe II, Bass CR: Impact responses of the cervical spine: A computational study of the effects of muscle activity, torso constraint, and pre-flexion. J Biomech, 2016; 49: 558–564.
10) Chawla A, Mukherjee S, MohanD, Jain SS: Validation of the Cervical Spine Model in THUMS, 19th Technical Conference on the Enhance Safety of Vehicles (ESV). Washington, D.C.: National Highway Traffic Safety Administration (NHTSA), 2005.
11) Kimpara H, Nakahira Y, Iwamoto M, et al: Investigation of anteroposterior head–neck responses during severe frontal impacts using a brain–spinal cord complex FE model. Stapp Car Crash J, 2006; 50: 509–544.
12) Myers BS, McElhaney JH, Doherty B, et al: Responses of the Human Cervical Spine to Torsion. SAE Publication P–227; Proceedings of the 33rd Stapp Car Crash Conference. Society of Automotive Engineers (SAE), 1989.
13) Pintar FA, Yoganandan N, Voo L, Cusick JF, Mainan DJ, Sances A: Dynamic Characteristics of the Human Cervical Spine. SAE Publication P–299; Proceedings of the 39th Stapp Car Crash Conference. San Diego, USA: Society of Automotive Engineers (SAE), 1995; 195–202.
14) Nightingale RW, McElhaney JH, Richardson WJ, Myers BS: Dynamic responses of the head and cervical spine to axial impact loading. J Biomech, 1996; 29: 307–318.
15) Ivancic PC: Cervical spine instability following axial compression injury: a biomechanical study. Orthop Traumatol Surg Res, 2014; 100: 127–133.
16) Kuster D, Gibson A, Abboud R, Drew T: Mechanisms of cervical spine injury in rugby union: a systematic review of the literature. Br J Sports Med, 2012; 46: 550–554.