Development of proactive anti-whiplash system through a combined computational and experimental approach

Kalish Gunasekaran[1], Yuze Li[1], Qi Zhang[3], and Haojie Mao[1, 2]

1. Mechanical and Material Engineering, Western University, London ON, Canada
2. School of Biomedical Engineering, Western University, London ON, Canada
3. Department of Pathology and Laboratory Medicine, Western University, London ON, Canada

ABSTRACT – The majority of anti-whiplash safety technologies currently in production need to be mended or replaced after each deployment, and they are not engaged until a collision occurs. Thus, the purpose of this study was to develop a proactive anti-whiplash safety system that utilizes a smart algorithm to instantaneously adjust the head restraint backset before a collision depending on the approaching condition from the rear vehicle. A total of 20 rear impacts with five different backsets and four initial seatback angles were simulated numerically using a human body FE model to investigate the influence of head restraint backset distance on cervical facet capsule joint (FCJ) strain during the impact. Experimental system testing was carried out in two driving scenarios using five volunteers. Our computational findings identified optimum seatback-angle-dependent backsets for specific scenarios and in future newly optimized backsets for testing scenarios can be easily updated in the developed physical system before a collision to reduce FCJ strain and mitigate potential whiplash injuries.

INTRODUCTION

Even though there is no clear pathology of whiplash injuries, previous cadaver and experimental studies identified the cervical facet capsule joint (FCJ) as the major focus for chronic pain after whiplash (Yoganandan et al. 1998, Ono et al. 1997). Previous literature shows that FCJ injuries most likely occur in lower cervical vertebrae within the C5-C6 and C6-C7. Human body FE models (HBMs) were found to be effective in studying FCJ injury mechanism. Kitagawa et al. (2006) modified the existing neck of the THUMS human body model to estimate FCJ tissue strain and demonstrated that relative displacement generated during the impact has a strong correlation with FCJ strain. Their subsequent research revealed that head restraint position, stiffness of the seat reclining joint and head restraint stiffness were relatively significant to reduce FCJ strain (Kitagawa et al. 2007). Furthermore, they reported that forward and upward movement of the active head restraint reduced FCJ shear deformation, which in turn lowered FCJ strain (Kitagawa et al. 2008). There is, however, a gap in the literature on understanding the influence of head restraint backset (the distance between the occupant's head and the head restraint) on FCJ strain development during a whiplash-relevant event. As a result, in this study, we numerically analyzed the effect of backset and seatback angle on FCJ strain development during low-speed (< 10 mph) rear impact.

Address correspondence to corresponding author Haojie Mao. Electronic mail: hmao8@uwo.ca

The objectives of this study were to numerically find optimized head restraint backsets effect on FCJ strain development during low-speed rear impact, and to experimentally develop a pre-collision whiplash safety system that can instantly adjust the head restraint backset based on the approaching conditions from the rear vehicle.

METHODS

Rear Impact sled assembly and simulation

THUMS (The Total Human Model for Safety) Whiplash V4.0 occupant model representing 50th percentile average adult male (AM50) was used to examine the joint capsule strain development (Fig. 1). The rear impact FE rigid sled assembly from THUMS V5.03 occupant model validation was used to simulate a rear end collision. A 6 km/h velocity curve based on the experimental data was prescribed to validate the sled assembly with whiplash THUMS model. Angular displacement data calculated from head CG relative to the ground was validated against test corridor (Ono et al. 1997).

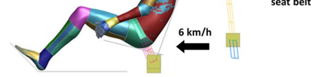

Figure 1. THUMS rear-impact simulation.

An isolated FE head restraint assembly from 2019 Honda Odyssey second row seat was included in the existing sled assembly to investigate the influence of the occupant head–to-head restraint distance on FCJ strain development during low-speed rear impact. A total of 20 rear impacts were simulated with five different backsets (0mm, 20mm, 40mm, 60mm and no head rest) and four initial seatback angles (15, 20, 25, and 30 degree). Time varying maximum principal strain of all FCJ parts between C2 and C7 vertebrae is calculated. ANOVA (analysis of variance) and Taguchi analysis were conducted to study the significance of backset and seatback angle on FCJ peak strain.

Development of proactive whiplash safety system

A retrofitted car seat was used, and the head restraint assembly (Figure 2a) was redesigned to mechanically push forward or retract the head restraint synchronously when the IoT (Internet of Things) powered control system is activated based on the relative distance from the striking vehicle. Ultrasonic sensor was installed into the head restraint and LIDAR sensor was placed inside the rear bumper to measure the head restraint-to-occupant's head distance and relative distance of the striking vehicle respectively. Mbed, a free-open source IoT operating system with connectivity and Arduino IDEs were used in this system. Using five volunteers with average backset values and basic information as illustrated in Table 1, the experimental system testing was carried out for two driving scenario with the striking vehicle's initial distance from the test vehicle set at 20 meters and its initial relative speeds set at 20 km/h and 7 km/h, respectively. Based on the hardware design and software algorithm improvement, two prototypes (Alpha and Beta) were further developed.

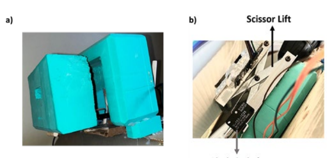

Figure 2. Experimental head restraint development

Table 1. Volunteer sitting posture measurement. Relaxed indicate participants sitting in a relaxed state whereas focused refers to volunteers sitting in a braced posture.

Volunteer	Gender	Height (cm)	Weight (kg)	Relaxed Seating Avg. (mm)	Focused Seating Avg. (mm)
1	Male	188	75	35	73
2	Male	184	85	42	64
3	Male	179	70	33	70
4	Female	169	57	25	65
5	Female	162	50	45	73

In Prototype Alpha, the head restraint deployment was upgraded from initial gear rack system to scissor lift, (Figure 2b) and the entire system was controlled by an Arduino Uno microcontroller to reduce the programming complexity. However, in Prototype Beta, the same hardware as Prototype Alpha was used with the primary improvement of filtering the noise from LIDAR sensor data using the Kalman filter to reduce the chance of false activation of the system.

RESULTS

FE Simulation Results

Influence of head restraint backset and seat back angle in FCJ strain development

Time varying strain data from all eighteen elements of FCJ parts between C2-C3, C3-C4, C5-C6 and C6-C7 cervical vertebrae were calculated for all simulations. (Fig. 3). Figure 4 illustrates the comparison of peak strain values of all FCJ element between C6-C7 under five different head restraint backsets and four seatback angles respectively. The least amount of strain at C6-C7 vertebrae occurred for the 15-deg seatback angle with a 20mm backset, the 20- and 25-deg seatback angle with 40mm backset, and the 30-deg seatback angle with a 60mm backset.

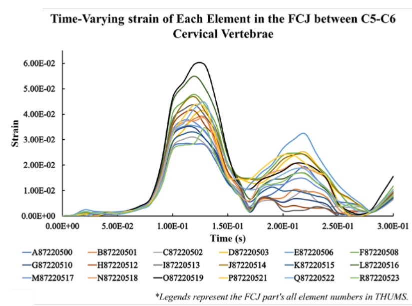

Figure 3. Strain time history of the FJC elements between C5 and C6.

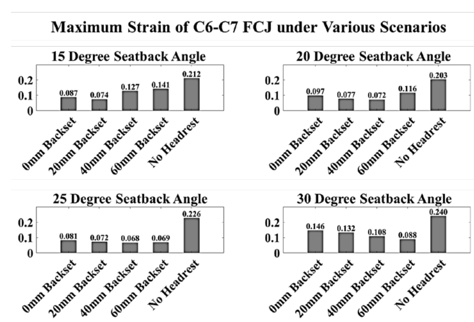

Figure 4. FCJ strains under various backsets and seatback angles

Experimental Design Results

Relationship between relative vehicle distance and head restraint backset

The experimental proactive system demonstrated its capabilities to adjust backsets to the desired gaps before a crash happens. For example, the backset of 20 mm and 40 mm were realized for 15- and 20-degree seat angles, respectively (Figure 5).

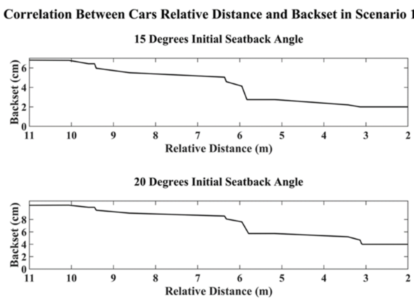

Figure 5. Typical backsets under 15- and 20-deg seat angles

DISCUSSION

Our simulation results indicated that FCJs between lower cervical vertebrae (specifically C5-C6 or C6-C7) were subjected to highest strain during low-speed rear impacts. These findings are consistent with previous studies which highlighted the potential risk of lower cervical vertebrae (Cusick et al. 2001). It's found that under various seat back angles, optimized backsets varied. However, one major limitation of current FE study is that we considered four seatback angles and one impact speed. Additionally, there was no variation in the head restraint design or position, occupant size or posture and the impact was in-line. The study findings are applicable to the scenarios examined and may not be applicable to other scenarios. Secondly, a rigid seat assembly is used which differs from the deformable seats in the real world. We expect that using real seat models and adjusting human body postures, the optimized backsets could change.

Using Kalman filter (detailed data not shown), Prototype Beta outperformed Alpha with effective noise filtered sensor reducing the probability of false activation of the safety system. Comparing the correlation plot for driving scenario I and II, we verified that the developed safety system successfully adjusted the backset at particular cutoff relative distance based on the approaching vehicle speed. Main limitation of the experimental safety system is the head restraint can move in the direction perpendicular to the head restraint stem with no vertical adjustment. The system may not perceive and activate when a vehicle approaches from outside the LIDAR's Field-of-View (FoV).

CONCLUSION

We developed a novel anti-whiplash safety system and its performance was evaluated through experimental testing. Using the human body FE model, we numerically investigated the effect of head restraint backset on FCJ strain during rear impact. We found optimized seatback-angle-dependent backsets through human body modeling, and developed a physical system that could realize these optimized backset gaps before a crash happens, minimizing the risk of whiplash. However, it should be noted that optimized backsets in this study were for specific, simple rigid-seat settings, and changes are expected with more accurate deformable seat settings. Meanwhile, the physical system could be conveniently updated in coding when newly optimized backsets are found in the future.

ACKNOWLEDGMENTS

We acknowledge NSERC Discovery program, Canada Research Chairs program, and New Frontiers in Research Fund – Exploration for financial support.

REFERENCES

Cusick, J. F., F. A. Pintar and N. Yoganandan (2001). "Whiplash syndrome: kinematic factors influencing pain patterns." Spine 26(11): 1252-1258.

Kitagawa, Y., T. Yasuki and J. Hasegawa (2006). A study of cervical spine kinematics and joint capsule strain in rear impacts using a human FE model, SAE Technical Paper.

Kitagawa, Y., T. Yasuki and J. Hasegawa (2007). Consideration of possible indicators for whiplash injury assessment and examination of seat design parameters using human FE model. 20th International Conference of the Enhanced Safety of Vehicles (ESV), Lyon, France.

Kitagawa, Y., T. Yasuki and J. Hasegawa (2008). "Research study on neck injury lessening with active head restraint using human body FE model." Traffic injury prevention 9(6): 574-582.

Ono, K., K. Kaneoka, A. Wittek and J. Kajzer (1997). "Cervical injury mechanism based on the analysis of human cervical vertebral motion and head-neck-torso kinematics during low speed rear impacts." SAE transactions: 3859-3876.

Yogananda, N., N. Yoganandan, F. A. Pintar, S. Kumaresan and A. Elhagediab (1998). "Biomechanical assessment of human cervical spine ligaments." SAE transactions: 2852-2861.