Dynamic Study and Analysis of Active Head Restraint Systems

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ABSTRACT

The purpose of this report is to delve into the safety systems that surround us everyday as we drive, and to analyze the benefits of these systems. Specifically, the active head restraint system is an often overlooked safety device common in many vehicles, and provides the capability for mitigating damage in rear-end collisions. There are many different types of active head restraints, each having comparative advantages and disadvantages. The differences between these systems are explained in detail, and a computer model is provided for clarification and analysis. An in-depth crash analysis was performed to assess the performance of these seats, and the results compiled from research papers are contained herein.

Keywords: active head restraint, rear-end collisions, crash analysis

SUMMARY

The measures used to correct our human malfunctions in today's vehicles are called safety devices. Specifically, these devices are split into two categories: passive and active. Passive devices react to driver behaviors after an event, while active devices change or correct driver behavior. In today's cars, there are hundreds of sensors used to compile data about the driving condition. Along with the myriad of sensors, many passive devices are installed into the vehicle, such as seatbelts and airbags. The combination of these many safety devices allows the car driving experience to be comparatively safe, drastically reducing annual casualty rates.

Active Safety Devices

Initially, active safety devices were simply methods to achieve a better driving situation. For example, a large driver windscreen and rearview mirrors are considered active safety devices. Nowadays, as more sensors are being introduced into vehicles, the term active safety device is gaining a new meaning. With the introduction of ABS, traction control, and blind spot sensing, cars' safety in active settings have drastically improved. By further computerizing the car, the errors due to the human driver can be corrected by the vehicles CPU.

Passive Safety Devices

In order to improve driver safety after a collision occurs (assuming an active safety device didn't avoid the collision), passive devices must continue to be developed. The most common of these are seatbelts and airbags, which continually get improved upon and most people are aware of. Volvo introduced three-point seatbelts over 50 years ago, after many failed tests attempting other designs [1]. Airbag systems, since their introduction in the early 1970s by Ford, have continually been improved upon drastically [2]. Initially only in front of the driver and passenger, nowadays airbag systems envelop the entire car in the case of collision. Figure 1 showcases this coverage. Notice the curtain airbags along the side windows, the side airbags on either side of the front seats, and the knee airbags in front of the driver. The complexity of this system allows for it to account for a multitude of collision types in order to maximize safety for the occupants.

Figure 1: Airbag system

Active Headrest: However, one passive device most people are unaware about is the active headrest system. AHS drastically reduce the number of head and neck injuries in rear end collisions, doing so by diminishing whiplash affects by up to 45% [3]. The device is actually extremely simple in concept. The goal of AHS is to cushion the head (and ultimately, the neck) in the event of a rear end collision. To do so, the headrest portion of the seat is moves in order to adjust to the head's relative position after impact. The first devices used were purely mechanical: no CPUs were used to turn data into mechanical motion. These devices used the lever motion between the seatback and headrest to deliver motion into the seatback to motion of the headrest [4]. Figure 2 shows how the headrest meets the head, by moving diagonally forwards and upwards.

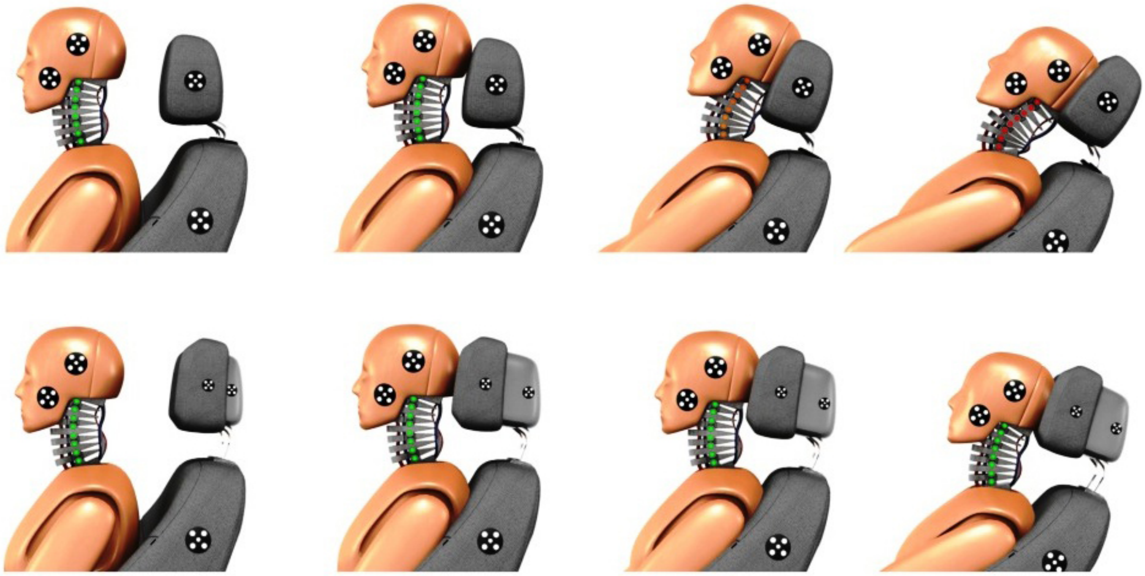


Figure 2: Active head restraint movement

Developments into active head restraints lead to a multitude of different design types over the last 15 years, after Saab introduced the first AHS in 1997 [5]. In 1999, Volvo introduced their WHIPS system [6]. An abbreviation for Whiplash Protection System, this device was similar to Saabs in that it was purely mechanical. However, the device uses a deformable metal plate in the seatback to absorb impact energy. Because this plate absorbs the energy and plastically deforms, the WHIPS system must be replaced after every impact. In 2003, BMW introduced an active head restraint in their E60 “comfort” seat package. Upon collision, sensors in the vehicle identify the situation and send signals to the car’s seats [7]. These signals trigger a pressurized explosion, accelerating part of the headrest forwards toward the occupant’s head. This system, much like Volvo’s WHIPS, must be replaced after every collision. Toyota introduced its WIL (Whiplash Injury Lessoning) system in 2012, attempting to improve on the previous competitors malfunctions. The WIL system uses a heavily cushioned seatback to deform to the body upon impact. This deformation in the seat then sends a signal to the headrest, which tilts diagonally forwards [8]. Recently, Chrysler has attempted to make improvement to the systems on the market with its electronically controlled headrest. The headrest functions by taking metrics from a myriad of sensors in the car. The CPU then determines the appropriate position of the headrest to minimize damage to the users necks. The headrest then deploys forward pneumatically in order to meet the persons head earlier (and with more dampening) than would be otherwise. In 2013, Chrysler had to recall more than a half million vehicles due to the possibility of a malfunctioning electronic headrest [9]. This shows that the most technologically advanced device is not always the safest: because the more intricate the design, the greater the chance for failure.

SAHR

The first active head restraint introduced to the market was Saab’s active head restraint system. The so-called SAHR was revolutionary for it’s safety improvements, and has remained heavily researched due to its simplicity. The SAHR is a purely mechanical system, with the rearward motion of the person’s body the driving force for the lever, which in turn sends the headrest forwards [5]: as seen in fig. 3. When the driver gets rear ended, the force from the collision sends the driver backwards into his seat. This force exerted is transferred through the lever to move the headrest forwards, meeting the head earlier than it would have and reducing the range of whiplash. The best attribute of this device is that the headrests dynamics are entirely dependent on the input. What is meant by that is that the harder the impact to the seatback, the more extreme the motion of the headrest. Because of this, the AHS system calibrates itself for every initiation.

Figure 3: SAHR system motion

Resultant Injuries of Rear-end Impacts

Because the active head restraint is designed to improve the crash performance in rear-end collisions only, the forces and injuries involved have a very narrow scope. Of the injuries encountered after rear-end collisions, 90% are neck injuries [3]. Because of this, extensive research has gone into the cause of neck injuries. Due to the complex structure of our necks, the mechanisms of injury are still largely unknown. However, researchers agree that the “s-bend” shape of the neck is consistent among all whiplash-induced injuries.

Mechanism of Injury: There are many theories as to the mechanism of whiplash within the neck, with varying degrees of complexity. One such mechanism involves the injury to posterior facet joints in the cervical spine [10]. The deformation of these joints is related to shear and extension of vertebrae, resultant of being subjected to rear end collisions. Another proposed mechanism of injury is the contraction-induced injury to the sternocleidomastoid muscle [11] and the extension-induced injury to the vertebral artery [12]. Injury to the musculature and ligaments, caused by contraction and extension of the cervical spine, may result in headaches and muscle pain [13].

Methods

In order to assess the degree of damage a certain collision may cause, an understanding of the mechanisms of injury is necessary. Once the proposed mechanisms are understood, a testing procedure can be put in place to determine the impact collisions have on these mechanisms. Data processing is then performed to analyze each collision scenario.

Test Methods

In the crash tests, the common procedure is to run a weighted sled into the rear of a stationary vehicle. The vehicle contains one or two crash dummies, each equipped with many strategically placed accelerometers and load cells. The most commonly used dummies among the following tests are the BioRID Hybrid III, as shown in fig. 4. The dummy consists of one load cell, four 2-axis accelerometers, and two 3-axis accelerometers. The load cell is mounted at the base of the skull, recording forces in the x and Z directions, as well as a moment about the y-axis. The 2-axis accelerometers are placed where the C4, T1, T8, and L1 vertebrae would be located in a human, recording accelerations in the x and z directions. The 3-axis accelerometers are placed in both the skull and pelvis. These dummies were positioned in both in (ip) and out of position (op). In positioned was determined to be the dummy along the seatback with the head 40mm from the seatback, with out of position being 250mm from the seatback [5]. All tests were run at a seat angle of 21° with respect to vertical.

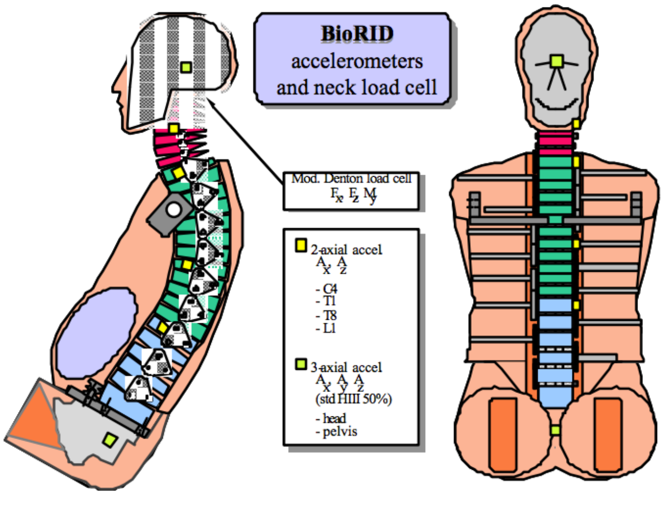


Figure 4: SAHR system motion

Analysis of Test Results

In order to take the data recorded by the BioRID dummy and convert it into useful information for safety analysis, post-processing methods must be established. Along with displacement and load values, the Neck Injury Criterion (NIC) was developed to determine the severity of neck dynamics [14]. The NIC predicts the pressure pulse in the spinal canal by means of measuring the difference in acceleration and velocity between the lower and upper part of the neck, as shown in equation 1:

$$NIC = [0.2a_x + {v_x}^2]_{OC-T1} \qquad (eq. 1)$$

Where a_x is the acceleration, and v_x the velocity, between the occipital condyles (or C1) and T1. The NIC has since been refined to the NIC_{50}, meaning the NIC value should be taken at moment the relative position between the upper and lower parts of the neck is 50mm [5].

FINDINGS

Upon further research and computer modeling, it was able to be determined that the most suitable active head restraint design is the SAHR for performance and crash analyses of the system. Beyond looking at the dynamic response of the head and neck, such as the relative displacements and angles to one another, models such as the NIC have been developed to determine the severity of such motion.

Mechanical Breakdown of SAHR

In order to analyze the motion of Saab's active head restraint, a 3D model had to be constructed using SolidWorks software. The initial goal was to obtain a used Saab car seat, either from a junkyard or an online auction and to reverse engineer the system. After weeks of deliberation, the search yielded no hits and the model was reduced to what was found in research papers. By utilizing the schematics found in multiple SAE documents, an accurate model was developed to simulate the motion of Saab's head restraint system. Figure 5 shows this model, in both the engaged and disengaged positions. The red component is the main lever of the system, transmitting the power from the seatback to the headrest. The lever connects to the seatback via mounting plate, and in the full system springs would be implemented to provide resisting force between this plate and the seatback. The lever then transmits the motion through a cam, which in

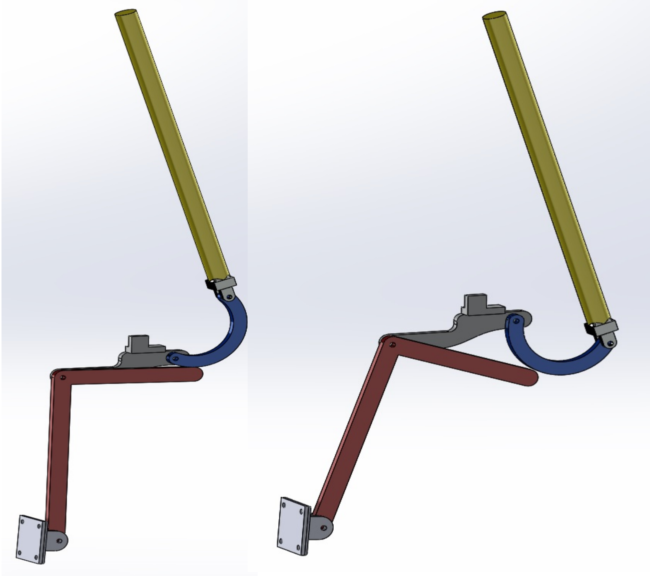


Figure 5: SAHR SolidWorks Model

turn extends a rod connecting to the headrest. An analysis of this model determined that a seat deflection of 10mm corresponded to a headrest movement of approximately 5mm upward and 4mm forwards, consistent with the SAHR implemented in vehicles [5].

Crash Analysis

When subjecting the crash dummy to rear-end collisions at different speeds, accelerations are recorded by the accelerometers implanted within the dummy. Along with force readings, this data is post-processed to determine injury criterion and the overall safety of the device.

Experienced Accelerations: For crash test purposes, tests were run at many different speeds and configurations. Standardized speeds of 12, 16, and 20 km/h were used for analysis. Figure 6 shows the acceleration experienced by the test sled for different test speeds. Furthermore, by using the sensors equipped in the dummy, data can be processed to determine the accelerations of each position of the body. Figure 7a shows the acceleration differences for the in position test, while fig. 7b shows the same result but for out of position. These results are both from a standard 12km/h test. Notice how in the ip test the acceleration of the lower neck is delayed compared to that of the chest, showing that the body is able to penetrate effectively into the seatback. More importantly, the head acceleration starts soon after the neck acceleration, meaning that the differential motion between the two is minimal. For the op test, the head accelerates later relative to the neck and chest, indicating larger relative displacements. Also, the accelerations experienced in the op test were nearly twice as high as the ip test [14].

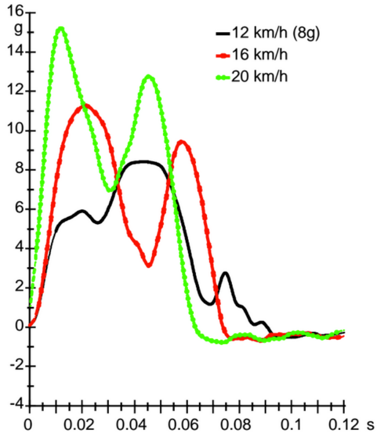
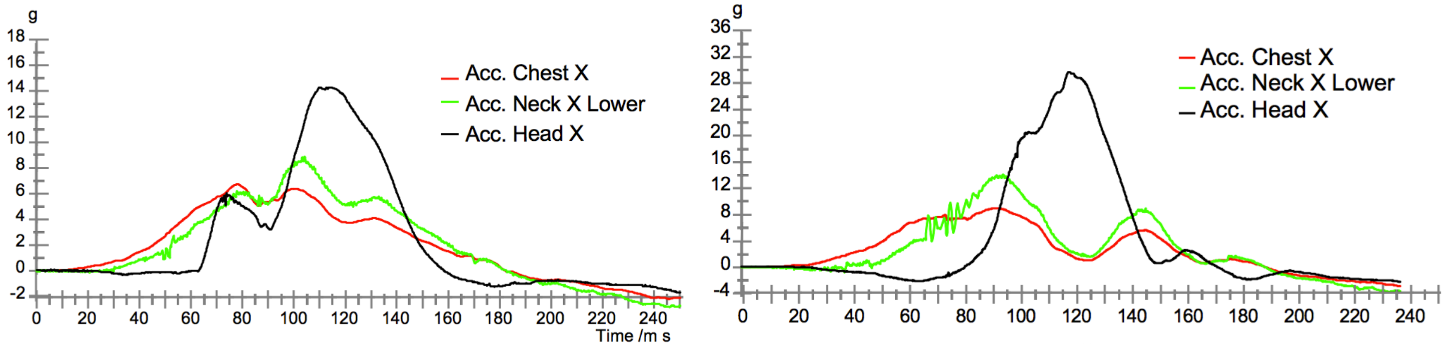


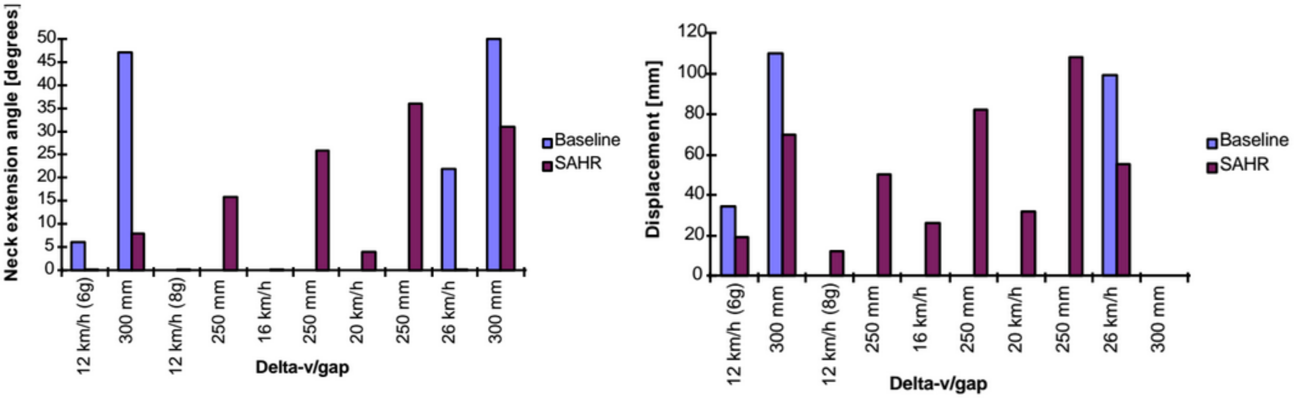
Figure 6: Accelerations of sled



(a) *(b)*

Figure 7: Accelerations for both ip and op tests

Experienced Displacements: Due to the relative accelerations of each portion of the body post-impact, each portion of the body displaces disproportionately to one another. Specifically, the angle the neck extends and the distance the head displaces are of interest. Figure 8a shows the extension angle of the neck relative to baseline (21°) [5]. The x-axis represents tests at different speeds, or out of position displacements at those speeds. The red bars represent the SAHR, with the blue bars being a baseline. The baseline was only run at 12 and 26 km/h, as well as 300mm out of position tests for those speeds. When in position, the only test that resulted in any angular displacement was the 20 km/h test; whereas the baseline seat resulted in more angular displacement at the slowest speed. Furthermore, for the out of position tests, the SAHR never achieved an angular displacement greater than the initial displacement of the head: with 250mm corresponding to a flexion angle of 33°. Figure 8b displays results from the same series of tests, with the y-axis now representing the displacement of the head relative to the T1 vertebrae (lower neck). The head displacements for the SAHR are around half that of the baseline seat in all tests. Again, for the out of position tests, the resultant displacement never surpasses the initial displacement of the head.



(a) (b)

Figure 8: Extension angle and displacement of head for ip and op tests

Neck Injury Criterion: By analyzing the crash data using the NIC formula aforementioned, an injury severity can be numerically established. Figure 8 shows the NIC vs. displacement of the lower neck, for two different tests. The grey line shows results from a 12 km/h in position test. Notice the neck never displaces to the 0.05m line, where the NIC_{50} number would be established. The black line represents the results from a 16 km/h out of position test, passing through the displacement line around a NIC value of 20 m^2/s^2. It is worth noting that none of the in position tests reached a lower neck displacement of 50mm. However, the vast majority of drivers drive in an out of position alignment, making it more suitable for real-word comparisons.

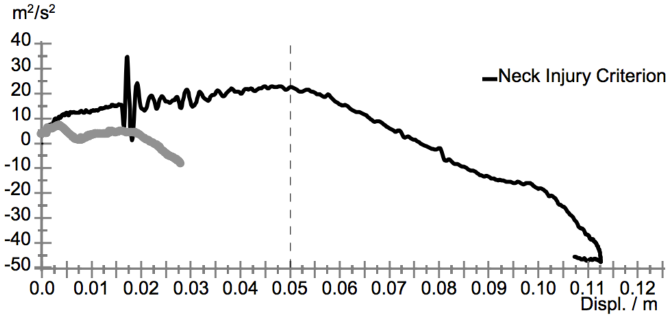


Figure 9: NIC vs. displacement for ip and op tests

Competitor Comparisons: In a different series of tests, the SAHR system was tested against a baseline; a modified baseline, using headrest that sits closer to the head; a cervigard seat, which is a contoured seatback mimicking the natural curvature of the spine; and the WIL [14]. Figure 10 shows the results of testing at 18 km/h with all seats besides the WIL.

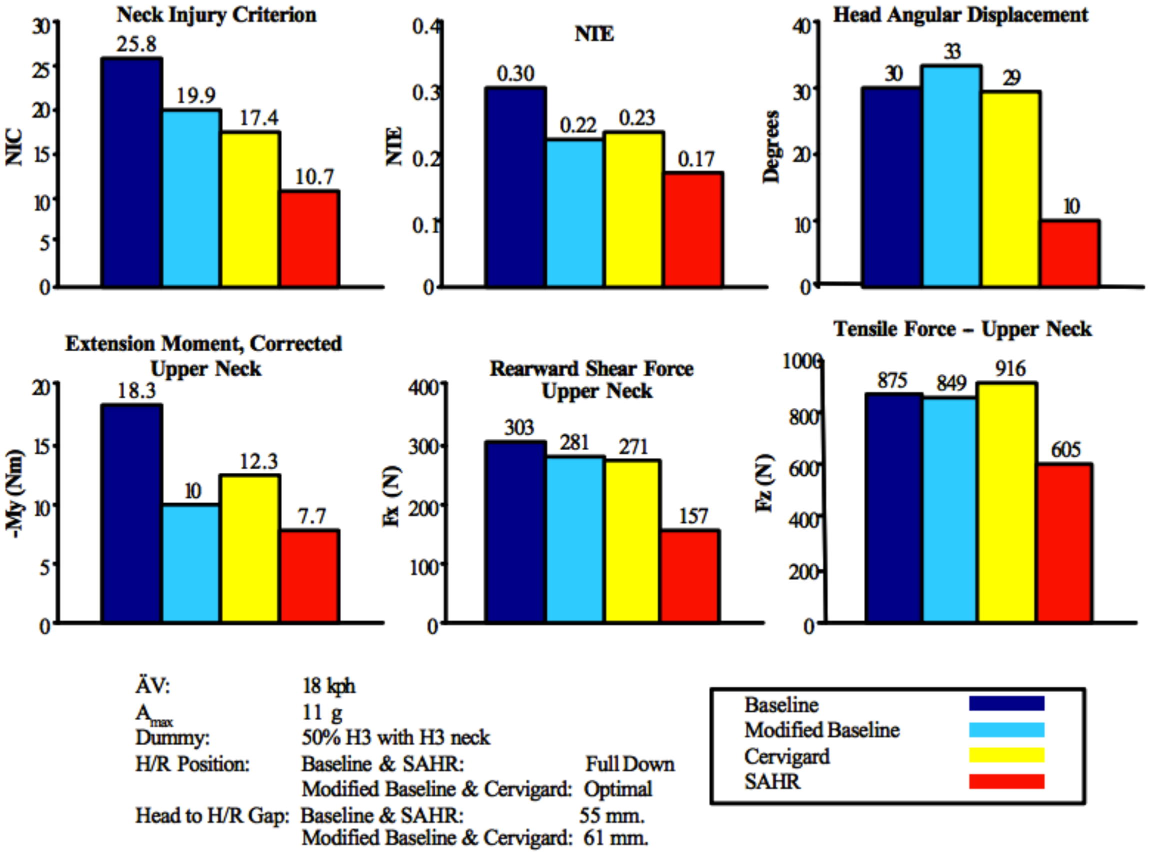


Figure 10: SAHR vs. various seat types

The SAHR shows significant improvements in NIC in comparison to all other seats, as well as a drastic improvement in angular displacement. Furthermore, the SAHR reduces the tensile and shear forces on the neck, as well as its moment. It’s interesting to note that the tensile force is reduced on the neck in the SAHR, because the headrest moves forward on impact to meet the head. Conceptually it would seem that this would cause greater tensile forces on the neck due to collision, but experiments show that the SAHR actually improves in this area. In comparison to Toyota’s WIL, the SAHR performs better across all categories. Figure 11 shows the data results from a test comparison with the WIL, all run at speeds of 24 km/h. The SAHR has nearly half the NIC and angular displacement of the WIL, and therefore also significantly improves upon differential speeds experienced by the neck. The speed of the lower neck relative to the head was drastically reduced by nearly four times at the highest NIC value, but the maximum speed achieved by the SAHR was more than half that of the WIL.

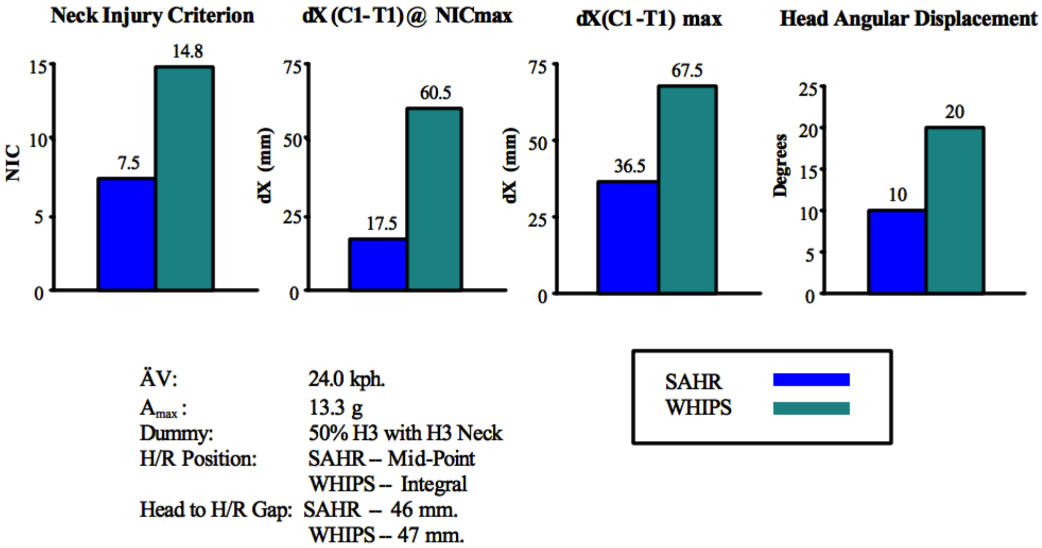


Figure 11: SAHR vs. WIL

CONCLUSION

Due to the frequency of vehicular accidents, safety measures implemented in cars are incredibly important for driver protection. Passive systems in these vehicles respond after a collision has taken place, often saving the drivers life before they have a chance to know what happened. Rear end collisions are not often life threatening, but 90% result in neck injuries that can be debilitating. Because of the prevalence of neck injuries in vehicle accidents, active head restraints have been developed to mitigate these damages. Based on test results, the SAHR system is a drastic improvement over baseline seats and performs better than some other rear-end collision safety systems. In nearly all tests the SAHR performed twice as well or better than the baseline system, successfully reducing the NIC, angular displacement of the neck, and speed at which the head moves relative to the neck. These test results indicate that the SAHR would drastically reduce injury in a real life situation, especially since the vast majority of drivers drive out of position.

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