REPLICATING REAL WORLD ROLLOVER CRASH INJURIES

Raphael Grzebieta
Mike Bambach
Andrew McIntosh
Garrett Mattos
Keith Simmons
George Rechnitzer
Transport and Road Safety (TARS) Research, University of New South Wales
Australia

Kennerly Digges
The George Washington University, National Crash Analysis Center
USA
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ABSTRACT

This paper details the injuries occurring in real world trip-over only rollover crashes, for seat belted and contained occupants, and assesses whether these injuries can be replicated using a Jordan Rollover System (JRS) crash test rig recently installed at Crashlab in Sydney. This research forms part of the Dynamic Rollover Occupant Protection (DROP) project funded by the Australian Research Council and industry collaborators to develop a dynamic rollover crash test protocol that can assess a vehicle's rollover crashworthiness. Australian National Coroners Information System (NCIS) fatality data and US NASS-CDS serious injury data of seat belted occupants involved in single vehicle pure rollover crashes ranging over the period of 2000 to 2010, were investigated. AIS3+ head and thorax injuries and AIS2+ spinal injuries were analysed to determine rollover injury characteristics and to determine possible test conditions under which they occur. Publically available dynamic rollover crash tests carried out by other researchers were also analysed to determine their capability of replicating these real world injuries.

Serious head injuries (SHI), serious neck/spine injuries (SSI) and serious thorax injuries (STI) were found to be distributed in roughly equal proportions, most occurring independently of each other, indicating different injury causal mechanisms. A significant portion of these injuries occurred where there was minimal or no roof crush involvement. Investigations of other researcher's crash test results show dynamic rollover crash test rigs, crash test protocols and anthropomorphic test devices (ATD) have not, in general, been able to replicate ATD loadings consistent with these real world injuries repeatedly in a manner similar to frontal or side impact crash test protocols. The dynamic test conditions, measurement systems (possible ATD) and criteria required to consistently replicate vehicle damage and a particular injury mode (SHI, STI and SSI) using the JRS are discussed.

It was concluded that to date it appears that current test protocols are not capable of consistently replicating the injuries identified in real world rollover crashes. Addressing roof crush alone via quasi-static testing will not mitigate all real world rollover injuries in typical trip-over only rollover crashes. A more advanced dynamic rollover crash test protocol must be developed that is more representative of the real world crashes and be capable of consistently replicating SHI, STI and SSI. It may be possible using the JRS test rig albeit the rig may need to be modified to tolerate much heavier impacts and a suitable rollover ATD may need to be developed. Until such time that the real world injuries observed in strong roof vehicles can be replicated repeatedly in a realistic manner, research on the development of an appropriate crash test protocol and ATD will need to continue.

INTRODUCTION

This is a summary of a paper which first appeared in the proceedings of the International Crashworthiness Conference ICRASH 2012 held in Milan Italy titled "The Dynamic Rollover Protection (DROP) Research Program" [1]. Readers are directed to the full paper for a more comprehensive discussion of the issues presented here.

A little more more than half of the single vehicle crash fatalities in Australia occur in passenger cars. Of these, about a quarter to one third of the occupants killed is in a vehicle that rolls over (n ≈ 150 fatalities per annum). Furthermore, rollover crashes account for: 12% of all Australian road fatalities; around 35% of all occupant fatalities occurring in a single vehicle crash injury event; around 17% of Australian spinal injuries; and are now greater in number than fatalities occurring in frontal or side impact vehicle crashes [2, 3].

Elsewhere, one in every three vehicle occupant lives lost in the USA is attributed to vehicle rollover crashes (around 10,000 fatalities), whereas around 10% of road users are killed in such crashes in Europe.

Australians have a very high seatbelt wearing rate ranging from 95% to 97% [4, 5]. Nevertheless, it appears around 60% of occupants killed in a rollover crash were found not wearing a seat belt [2, 3]. This has contributed to the Australia Federal and State governments to consider seat belt interlocks in their National Road Safety Strategy [6]. In regards to crash severity, Fréchède et al [2] found that around 83% of Australian rollover crashes occurred within two or less full rollovers (eight ¼ turns). Earlier studies of US crash data by Digges and Eigen [7] also revealed that around 90% of seriously injured non-ejected seat belted occupants occurred in two or less full rolls.

A number of studies to date have found a positive relationship between the amount of roof crush, roof strength and the likelihood of serious injury in rollover crashes [2, 3, 8-16]. However, the forty year debate on this issue still continues to this day. For example, Funk et al, Moffat and Padmanaban, Padmanaban et al, [17-19] and others continue to opine that there is no significant relationship between vehicle roof strength and injuries occurring in rollover crashes. One of the confounding factors in some analyses has been the inclusion of serious injuries to all body areas in an analysis, rather than injuries to specific regions. While there might not be a relationship between serious thoracic injury (STI) and roof crush, a relationship exists between serious neck injury and roof crush. Recent studies by Bambach et al, Mattos et al and Funk et al [15-17, 20] of contained and restrained occupants involved in single vehicle pure rollover crashes that occurred in the United States indicate that serious injuries to the thorax, head and spine can still occur even when there is little or no roof crush, highlighting the need to improve occupant safety systems.

While a strong roof with an SWR of 4 or more reduces the risk to almost zero in terms of a seat belted occupant being killed in rollovers that are representative of two roll or less pure rollover trip-over crash on relatively flat terrain, serious injuries can still occur [3]. It is not entirely clear how these injuries arise but they appear to be occurring from some form of impact with the interior due to velocity differentials. So far, replicating the real world injuries both in simulations and crash tests has been sporadic and inconsistent. Batzer [21] discussed some of the issues concerning experimental observations of sporadic injurious loading and relationship to real world crashes for different rollover test rigs.

The Dynamic Rollover Occupant Protection (DROP) research program, funded by the Australian Research Council via an industry linkage partnership, aims to establish which combination of vehicle rollover crash severity, roll kinematics, biomechanical injury criteria, and crash test dummy, best replicate the major proportion of rollover fatalities and serious injuries occurring to seat belted and restrained occupants in a typical 2 roll or less pure trip-over rollover crash over relatively flat terrain. The project industry partner organisations include BHP Billiton, Centre for Road Safety at Transport for NSW, the Transport Accident Commission, the Office of Road Safety at Main Road Western Australia and the US Center for Injury Research. Research centres involved in the project are TARS UNSW, Neuroscience Research Laboratories at the Medical College of Wisconsin, BAARG at University of Bolton, NCAC at George Washington University, and School of Biomedical Engineering and Sciences at Virginia Tech.

The outcomes of this three to four year research program will be an understanding of those factors most important for regulators, industry and consumer groups to consider when developing a dynamic rollover crashworthiness compliance or consumer rating crash test protocol. The DROP team will then determine which vehicle components (roof strength, roof geometry, restraint systems, air curtains, etc.), or combination thereof, provide the most effective, practical, and cost efficient rollover injury mitigation strategies for regulators, industry and consumers to consider and adopt. As has been seen in frontal and side impact crashworthiness, relevant dynamic crash tests with a focus on occupant protection bring many public benefits in terms of injury reduction and improvements in vehicle crashworthiness.

This paper presents the research program and progress on some of the sub tasks from the DROP program. In particular, investigations of how head, chest or thorax fatal injuries that occur to restrained and contained occupants are to be replicated for a reasonable severity rollover crash, will be outlined. The advanced UNSW version of the Jordan Rollover System (JRS), recently built and installed at Sydney Roads and Maritime Services Crashlab test facility is also described in a sister paper [22]. The JRS can carry out rollover crash tests for parametric studies where different aspects of the roll event can be precisely isolated and the results compared to analysis and computer simulations.

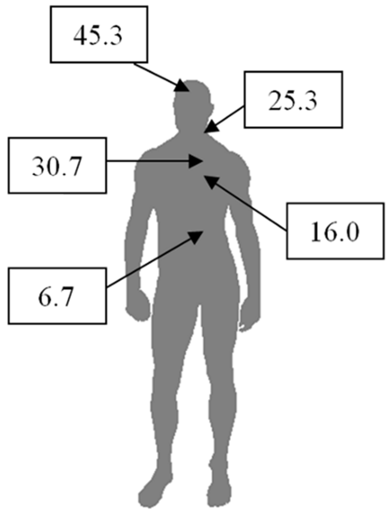

Figure 1. Percentage distribution of cause of death established from Australian NCIS data (after Fréchède et al [2]).

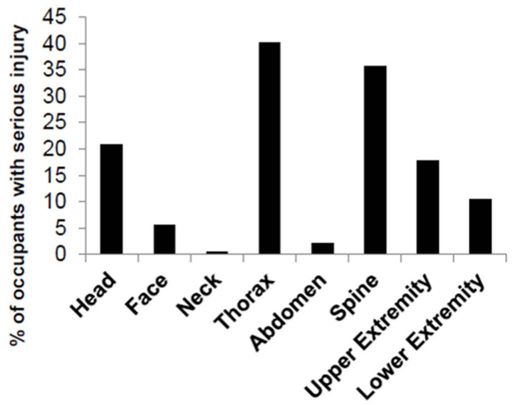

Figure 2. US NASS-CDS serious injury data (after Mattos et al [15]).

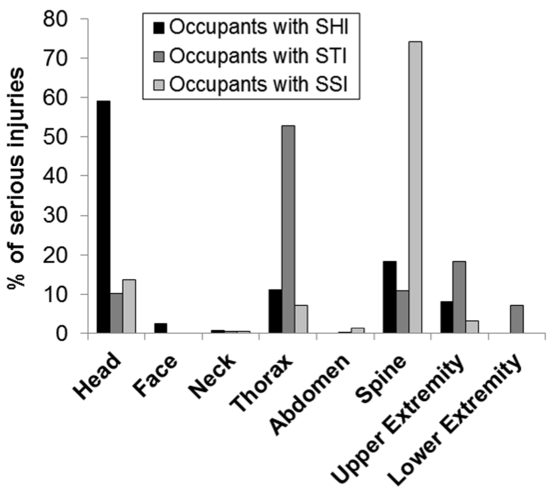

Figure 3. Distribution of occupants with serious injuries AIS 3+ by body region for contained, restrained occupants greater than 16 years old in pure, trip-over rollovers (after Mattos et al [15]).

TAXONOMY OF ROLLOVER INJURIES

Figure 1 shows results of recent studies by Fréchède et al [2] of Australian National Coroners Information System fatality data between 2000 and 2007 of 474 rollover cases, and Figures 2 and 3 show results of analyses from Bambach et al [16, 20] and Mattos et al [15] of US National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) serious injury data of contained and restrained occupants involved in single vehicle pure rollover crashes ranging from 2000 to 2010 (n=1009 unweighted) for pure trip-over rollovers.

The injury distributions indicate that serious head, neck/spine and thorax injuries appear to be distributed in roughly similar proportions. Furthermore, Mattos et al [15] have determined from their study of AIS 3+ injuries in NASS-CDS data over the period of 2000 to 2010, that the majority of serious head injuries (SHI) appear to occur independently to serious thorax injuries (STI) and serious spine injuries (SSI) (Figure 3). Around 70 % of occupants with SHI had neither a SSI nor STI. Also, 85% of occupants with STI had neither SHI nor SSI. Further, 82% of occupants with SSI had neither SHI nor STI.

The fact that a large portion of head and neck injuries usually occur independently of one another, and possibly have different mechanisms, was first noted by Friedman and Friedman [23] in 1998 and then confirmed by Atkinson et al. [24], Hu et al. [25] and more recently by Funk et al [17].

This fact has assisted the DROP team to decouple the SHI, STI and SSI and treat them as separate mechanisms in terms of research approach.

DROP RESEARCH PROGRAM

The Dynamic Rollover Occupant Protection (DROP) research program was developed as a result of successful research grant submitted to the Australian federal government’s Australian Research Council’s (ARC) Linkage Project grants scheme (No: LP110100069). As a result of the analyses carried of the NCIS and NASS-CDS data (Figures 1 to 3), the DROP program research has now focussed on replicating each of the thorax, head and spinal injuries observed in real word data as separate sub-tasks. Figure 4 shows a flow diagram of the process.

Currently finite element simulation is being used to determine how the injuries occur in vehicles for specific NASS-CDS cases. Work on replicating thorax injuries for selected cases has already commenced and preliminary results are being presented in another sister paper by Digges et al [26]. Work has also begun on simulating selected head injury cases. Once the injury mechanism and precise rollover conditions have been established, a computer simulation that models the UNSW JRS, vehicle and occupant represented by a suitable Anthropomorphic Test Dummy (ATD) will be carried out to assess whether the injury mechanism can be consistently replicated using the JRS. The protocol conditions used to apply the biomechanical impact loads that would likely result in any particular SHI, STI or SSI, will be noted. Biomechanical ATD and cadaver tests will be carried out if required to address research gaps regarding the ATD.

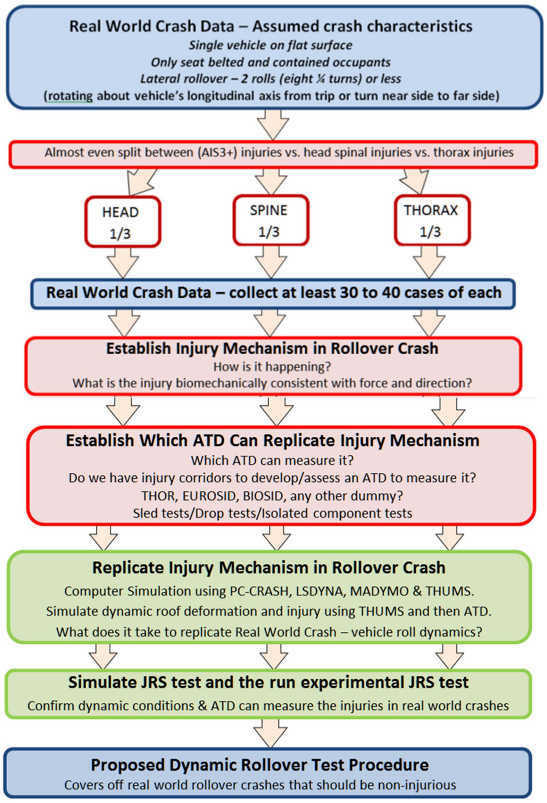

Figure 4. Dynamic Rollover Protection (DROP) program.

The starting point of the analyses replicating real world rollover crash injuries, is that all occupants are assumed to be abiding by the law in accordance with the safe system principles [6], i.e. occupants are all wearing a three point seat belt, travelling within the speed limit, and through no fault of their own are suddenly involved in a crash (e.g. swerving away from an errant oncoming vehicle). It follows that the law abiding driver (and other occupants in that vehicle) wearing an appropriately fitted restraint, should not die or be seriously injured as a result of the crash event. Presently some manufacturers have not been able to ensure occupants will not suffer permanent injury in rollover crashes of reasonable severity, i.e. two or less rolls over relatively flat terrain, mainly as a result of all the uncertainties in regards to understanding and replicating real world rollover crash injury mechanisms.

The second starting point for the DROP research program is to assume the vehicle's roof has an SWR that is rated 'good' by the US Insurance Institute of Highway Safety [27], i.e. SWR is equal to or greater than 4. Roof strength plays an essential part in the rollover crashworthiness design of vehicles. Limiting intrusion into the occupant compartment during a crash is critical in order to provide sufficient space for the occupant restraint systems to function and assist with occupant ride down decelerations. Analyses to date indicate when the roof structure is strong and the occupants are restrained by a three point seat belt, deaths and a large majority of the injuries in single vehicle rollover crashes are eliminated [3, 8, 9, 27, 28]. To mitigate those injuries which occur for roofs where SWR ≥ 4 in a reasonable severity two roll or less crash on relatively flat terrain, the team will consider injury cases where there is no obvious roof deformation over the occupant as a proxy that roof crush was likely not causal to the injuries imparted to the occupants.

Replicating injuries that occur in vehicles where SWR ≥ 4 presents a considerable challenge to the DROP researchers. None of the tests carried out to date in either the JRS or the Malibu II test series reported by Friedman and Grzebieta [29] and Bahling et al [30] have generated the accelerations of a magnitude that would indicate potential injuries as observed in some real world cases in terms of head and thorax injuries where there is little or no roof crush above the occupant. For example, to assess if the Hybrid III crash test dummies are capable of replicating injuries from real world rollover cases in simulated dynamic rollover crash tests, thirty-three head impacts, 15 for the near and 18 for the far side Hybrid III test dummies, were analysed from the Malibu II data FMVSS 208 dolly rollover tests and 26 impacts were analysed in the US Center for Injury Research (CFIR) JRS series of tests for all cases of roof deformation [28]. Analysis of the data found the maximum HIC_{36} was 268 from all JRS tests and 400 from all Malibu II roll-caged vehicle tests. Unfortunately chest injury data was not measured but it is assumed the accelerations would be low [29, 30].

Thus it appears the current test protocols using the FMVSS 208 dolly rollover test and the CFIR JRS and Hybrid III crash tests dummies have not been capable of consistently measuring observed real world head and thorax injuries. Batzer [21] provides some arguments as to why this may be occurring. It needs to be pointed out though, that the CFIR JRS tests and protocol have been entirely focused on demonstrating how the lower neck and associated spinal cord injury occurs and has shown some experimental correlation with roof crush [10, 29, 31-33]. Considering that head, spine and thorax injuries appear in the majority to occur independently, it is not surprising that the CFIR JRS tests, dummy and protocol do not replicate head and thorax injury. However, the main issue is that any dynamic testing using the JRS and Hybrid III crash test dummy adopting the current test protocols as proposed in Friedman and Grzebieta [29], will likely not be capable of replicating the injuries identified in vehicles with SWR $\geq$ 4. Thus a new test protocol must be developed that is more representative of real world crashes where head and thorax injuries occur.

It is worth noting that papers reporting on the Controlled Impact Rollover System (CRIS) indicate the CRIS rig is capable of producing head loads in ATDs that would be fatal to humans. However, Batzer [21] points out that the super-elevation of the vehicle's centre of gravity by more than a metre by the CRIS is not representative of uncomplicated ground level rollovers. Moreover, the trajectory of the vehicle, stripping of the inside lining, and the pre-positioning of the dummy orientation of the ATD with tethers, and release of the vehicle such that it impacts the roof directly over the occupant, has been tuned to demonstrate a diving injury impact event. Neither the wheels nor side opposite to the impact side contact the ground when the vehicle is released prior to head strike. As a result, the input to the head and neck of the dummy is very large and when viewed in totality appears unrealistic [21, 34]. Nevertheless, Friedman and Hutchinson have shown that the same loading can be replicated using the JRS [35]. It thus appears that the rollover kinematics induced by the test rig attempting to replicate the real world trip event and associated serious injuries is also a critical component to assessing the rollover crashworthiness of a vehicle.

Another issue regarding trying to replicate head and thorax injuries that typically occur in real world crashes concern the use of Hybrid III test dummies in dynamic rollover tests to assess potential injury risk. Paver et al [36] and Frechede et al [37] have also indicated issues concerning the Hybrid III's overly stiff neck. Anecdotal evidence indicates that the ATD must be capable of articulating the shoulders relative to the lower torso and hip and the neck may need to be more flexible than the current Hybrid III's neck flexibility. This motion is demonstrated in a rollover crash purportedly of a Volvo vehicle just outside Warsaw

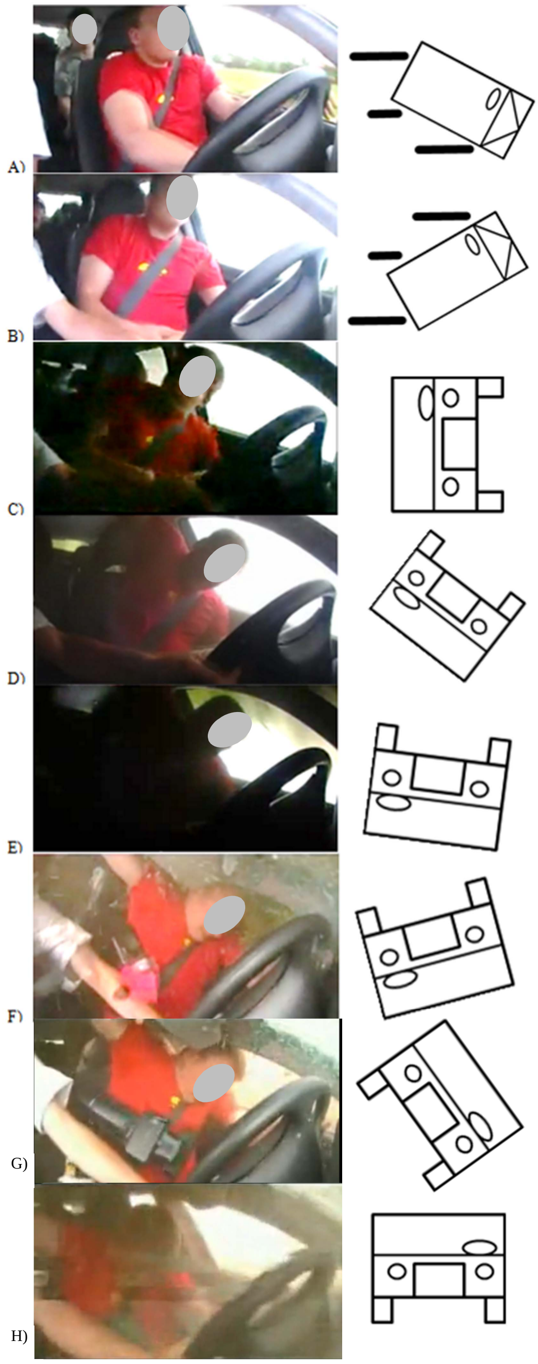

Figure 8. Driver view interior frames from a rollover crash caught on video with figures describing vehicle motion [38].

Poland that was caught on video and posted on YouTube (Figure 8). While detailed information other than what is seen on the video was not available to the Authors, this real world video nevertheless was a useful indicator of some of the possible injury mechanisms the authors are exploring. The following subjective observations are taken from this video.

The frames shown in Figure 8 appear to be an interior video within the vehicle of a pure trip only rollover consisting of 4 quarter turns [38]. The video from the camera mounted facing the driver, starts with the vehicle being driven down a road. The event begins when the driver swerves and puts the vehicle into a clockwise yaw (A). He then over corrects and the vehicle moves into a counter clockwise yaw (B). The difference in head position between (A) and (B) is worth noting. The driver maintains visual contact of the approaching road on the near side of the vehicle. Also note that the passenger has taken hold of the steering wheel.

In (C) (looking at the front of the vehicle now in frames C to H) we see the vehicle at around 1 quarter turn. The passenger is still gripping the steering wheel. The driver, who is the far side occupant, is being forced towards the window likely as a result of inertial centrifugal force and would have been ejected if not wearing a seat belt and the window was open. The sash part of the seat belt starts to compress into the shoulder. The driver also continues to maintain visual contact with the approaching road through the near side window.

In (D) it appears that the angular acceleration of the vehicle has completely overcome the occupant's muscle strength. The inertial centrifugal force coupled with the opposing force of the seat belt sash restraining the occupant's left shoulder in the vehicle causes his torso, shoulders and head to be tilted towards the window and B-pillar and away from the approaching road. The centrifugal force is so great against the belt restraining the left shoulder that the driver's shoulders are now parallel to the B-pillar. The inboard side of the driver's head is exposed to the roof rail. The seat belt is applying pressure to driver's shoulder and likely the clavicle and the shoulders appear to be tilted parallel to the B-pillar. The pressure applied to the driver's shoulder is evidenced by the embedment of the seat belt into the driver's soft tissue. In (E) we see the driver's head just before it makes contact with the roof rail at approximately 170 degrees of roll. The driver's shoulders are still tilted in line with the B-pillar. The inboard side of the driver's head makes contact with the roof rail in (F) when the vehicle's far side header rail strikes the ground. Note the compression of the seat belt into the shoulder and torso.

As the vehicle rotates back onto its wheels from (G) to (H), the driver is thrown across the vehicle, interacting with the centre console and the seat belt is restraining him from being thrown onto the passenger side, not dissimilar to how an occupant is thrown in a far side impact. This kinematic mode is discussed in detail in the Digges et al sister paper [26].

It is also worth noting that this compression of the seat belt acting on the driver's shoulder, resisting the inertial centrifugal force, may contribute to or cause clavicle fractures, chest compression with associated rib fractures and possibly lower lumber spinal injuries in occupants that suffer a torso injury in more severe rollovers. Such injuries have been observed by Bambach et al [20] where they state: "*40% of individuals that received serious thoracic injuries from door impacts in pure rollovers, also received injury to the shoulder region on the same side as the thorax injury. These included shoulder contusions (AIS1), clavicle fractures (AIS2), scapula fractures (AIS2) and acromioclavicular joint dislocations (AIS2). Around half of these injuries were attributed to the seatbelt, with the remainder attributed to contacts with the door or B-pillar.*"

This anecdotal evidence from the YouTube video indicates that in order for an ATD to appropriately replicate serious head, thorax and spinal injuries, it will likely require a flexible spine that allows the shoulders to dip and articulate in the manner as observed in Figure 8. With the recent advances and activity in Naturalistic Driver Studies [39] where drivers are observed by cameras, it may be possible to collect further video evidence of occupants during a rollover crash to establish their interactions with vehicle interiors and seat belt restraints and possibly air bags if they fire and stay inflated during a rollover crash.

CONCLUSIONS

The following conclusions can be made from the above:

- Latest investigations of US NASS CDS and Australian NCIS data indicate that serious head, thorax and spine injures in the majority appear to occur in roughly equal proportions and that they occur more or less independently of each other in terms of injury mechanisms. This indicates that each injury type can be independently researched to establish how they occur in vehicle rollover crashes of reasonable severity, i.e. two rollovers or less on a reasonably flat terrain. Solutions could be explored such as for example, if the roof is sufficiently strong (SWR $\geq$ 4) and side air-curtains and airbags are made to fire and maintain inflation during a rollover, this combination could substantially reduce the incidence of both thorax and head injuries. However, the optimum designs for rollover safety systems need to be proven both numerically and experimentally using for example the JRS test rig and a suitably bio-fidelic ATD.

- To date the CFIR JRS tests and test protocols used and proposed have been entirely focused on demonstrating how lower neck and associated spinal cord injury occur [10, 29, 31, 32, 33]. Test rigs based on the JRS and CRIS rigs appear to be capable of repeatable dynamic testing [29, 34, 35, 40] but these devices still require further analysis to define a range of protocols that best reflect real-world crashes with injuries [21]. Particularly challenging is the capacity of the new UNSW JRS rig's ability to replicate a crash of sufficient severity that characterise the loading conditions where thorax lung contusions and rib fractures are likely to occur.

- The current Hybrid III ATD is not capable of adequately reflecting the movement and impact responses that result in injuries in reasonable severity rollover crashes considered in this paper. It appears that the ATD must be capable of measuring thorax and head injuries similar in nature to that which occurs in side impact crashes, possesses a clavicle and rib structure capable of measuring forces which indicate fracture risk, and have an articulating spine and less stiff neck which results in shoulder and head movement that is reflective of real world human behaviour. In essence a multi directional crash test dummy will likely be required.

- Until such time that the real world injuries observed in strong roof vehicles can be replicated repeatedly in a realistic manner, research on the development of a suitable rollover crash test dummy and appropriate crash test protocol will need to continue.

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