The Role of Accident Investigation in Biomechanics Research

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Abstract Primary research on the biomechanics of impact often informs accident investigation. Such research is the source of nearly all data on human injury tolerance, is the basis for the development of most biomechanical modeling techniques in common use, and provides crucial information on the performance of various occupant protection systems currently installed in vehicles. This paper utilizes a recent aviation accident study to highlight the ways that accident investigation contributes to, complements, and guides biomechanics research. Aside from the basic collection of epidemiological data on injury in vehicular crashes or other accident scenarios, accident investigation can provide detailed information regarding the effectiveness of injury countermeasures in real world situations, evidence of unintended consequences of such countermeasures, effects of population variation on injury causation, and assessment of actual (as opposed to nominal) use of various systems designed for end-users, among other information. In addition, accidents may serve to highlight issues that might otherwise get little attention. While this attention may not directly drive primary research, it certainly provides an important input into vehicular design issues. Ultimately, the importance of accident investigation in biomechanics research may be to help focus the question of why the research is important in the first place.

Keywords Accident investigation, airbags, aviation, biomechanics.

I. INTRODUCTION

In 1948, Dr. (Captain) John Paul Stapp first demonstrated that seated humans (or at least one human, namely Dr. Stapp himself) could tolerate 35 Gs of deceleration in the longitudinal direction [1]. This was a fairly remarkable finding, as military aircraft at the time were being designed to an 18 G ultimate load factor [2], with many scientists believing that this was the limit of human tolerance. Dr. Bertil Aldman, in his 1962 doctoral thesis, evaluated methods for the experimental assessment of 2-, 3-, and 4-point restraint performance and biomechanical deformation in mechanical and animal surrogates [3]. Data from experiments such as these were critically important to the subsequent understanding of human biomechanics in accident investigation. It is worth noting, however, that Dr. Stapp's initial deceleration research "was planned and organized to answer such questions as, why one person is killed – and another not injured – in the same aircraft accident" [4], and that Dr. Aldman's thesis noted that he had surveyed police investigating accidents in Sweden who "were of the opinion that accident cars are not very often equipped with safety belts and that when they are the belts are not very often used." Thus these early researchers were influenced by issues originally identified in accident investigations.

When accident investigators are evaluating injury causation, they turn to data developed over more than a half-century of research into human tolerance to impact injury. They may utilize instrumented dummies and computer modeling techniques that have been refined through intensive laboratory testing and development. They benefit from data collected in large series of tests of the functioning of common occupant protection systems under a multitude of conditions. The art and science of accident investigation have clearly profited from the data and techniques developed by those doing basic research in the field of biomechanics; this paper proposes that, conversely, the investigation of vehicular accidents has important implications for the biomechanics research field. These implications will be discussed in the framework of a recent U.S. National Transportation Safety Board (NTSB) study of airbag performance in noncommercial aviation accidents over the

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past three years, in which the author participated [5].

II. METHODS

The use of accident data for epidemiological studies in assessing various biomechanical hypotheses is a well-established method for research in the field of impact injury. Large scale studies of crashes often have sufficient power to evaluate the association of multiple variables with injury outcomes. Epidemiological studies have been used over the last 5 decades to assess the effectiveness in automobiles of three-point restraint systems, airbags, and child safety seats, among myriad other evaluations [6],[7],[8]. These studies are often limited by the quality of the data collected, or by an inadequate number of accidents available that assess the variables of interest. Potential limitations of one of the largest databases, the U.S. Fatality Analysis Reporting System (FARS), have been described in previous publications [9],[10],[11] and it is at least in part due to these types of limitations that the U.S. National Highway Traffic Safety Administration also funds fairly detailed investigations of a sampling of accidents through the National Automotive Sampling System (NASS) and the Crash Injury Research and Engineering Network (CIREN). In many circumstances, the sheer volume of cases available for data analysis can help to identify or overcome potential problems. However, when the variable of interest involves a recently deployed technology, or is in a mode with a limited number of accidents to begin with, the number of cases may simply be insufficient to bring epidemiological techniques to bear. In such situations, the most effective method to gather information may be the detailed investigation of each case encountered in order to attempt to assess the potential role of various factors in the causation or mitigation of injury.

In 2003, airbags were first certificated for use on non-commercial (also known as general aviation or GA) aircraft, and as of June 2011, they have been installed in nearly 20,000 seats in approximately 8500 GA aircraft [12]. Unlike automotive airbags that typically deploy from the steering wheel, instrument panel, or above the window, airbags in GA aircraft are installed in the lap belt or shoulder harness portions of the restraint system and are designed to deploy outward from the pilot or occupant. Sled tests conducted under controlled conditions (See Figure 1) have suggested that aviation airbags may increase survivability and reduce injury in actual aviation accidents; however, no systematic evaluations had been conducted to evaluate their efficacy in real world scenarios. Therefore, in 2006, the NTSB initiated an exploratory case series study to assess airbag performance in GA accidents. The goals of the study were to examine the effectiveness of airbags in mitigating occupant injury in GA accidents, to identify any unintended consequences of airbag deployments, and to develop procedures to assist investigators in documenting airbag systems in future investigations.

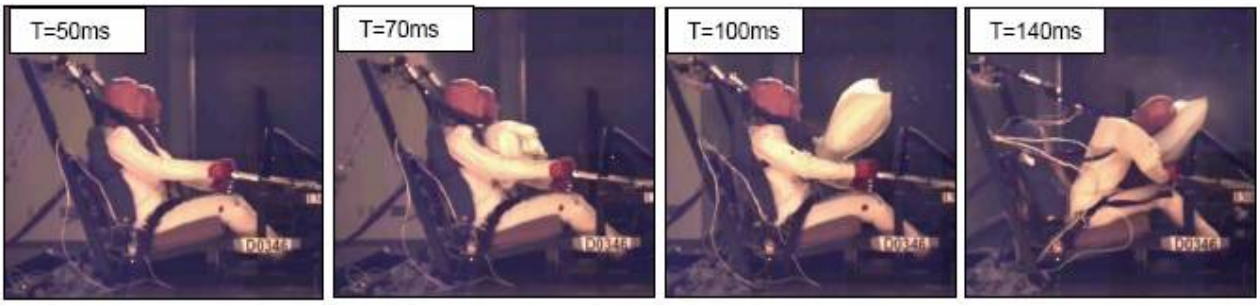

Fig. 1. General Aviation airbag sled test deployment sequence (screen captures of high-speed videos from dynamic testing – photos courtesy of AmSafe, Inc., used with permission)

Data collection began in August 2006 and ended in July 2009. Cases were defined as survivable accidents or incidents involving an airbag-equipped GA airplane (1) in which an airbag deployed, (2) involving occupant injuries but no airbag deployment, or (3) involving an inadvertent airbag deployment. There were 145 notifications of accidents or incidents involving airbag-equipped airplanes during the 3-year study period. Of the 138 events that occurred in the United States (21 involving fatalities), 19 were excluded from the study sample because they were determined to be non-survivable, and 3 were excluded because of missing evidence. Among the 117 survivable events, there were 7 accidents with airbag deployments, there were 3 accidents with

no airbag deployments but in which occupants sustained injuries due to the crash, and there were no inadvertent airbag deployments. These 10 accidents (involving 25 occupants) met the study criteria and were subjected to a full investigation, review, and analysis by a multidisciplinary team of accident investigators.

III. RESULTS

The NTSB's study concluded with the following 10 findings:

1. Based upon investigations of 10 accidents, there were no cases in which the airbags were expected to deploy but did not.
2. There were no cases that involved airbags deploying under unexpected circumstances. Based upon investigations of 10 accidents, there was no evidence of airbags hindering egress, fueling postcrash fires, or interfering with rescue attempts.
3. Aviation airbags can mitigate occupant injuries in severe but survivable crashes in which the principal direction of force is longitudinal.
4. Based upon investigations of 10 accidents, the airbag systems did not cause any negative outcomes when occupants adjusted the restraint systems correctly, and in some cases with airbag deployment, they were associated with reductions in the severity of occupant injuries.
5. Some general aviation occupants have misused or incorrectly adjusted their restraints in ways that could reduce the protection conveyed by the restraints or lead to injuries.
6. The 3-point restraint systems in certain Cessna Aircraft Company airplanes can be reversed by occupants in such a way that the airbag and restraint systems are not used as designed and certified.
7. Certain aviation airbag restraint configurations do not provide optimal protection for occupants whose anthropomorphic characteristics are substantially dissimilar to those of the anthropomorphic test dummy required for restraint testing.
8. Lap belt/shoulder harness combinations provide significant protection beyond a lap belt alone, and fatalities and injuries would be reduced if lap belt/shoulder harness combinations were used in all general aviation airplanes.
9. The understanding of aircraft crash dynamics and occupant safety would be improved if airbag-equipped aircraft recorded, at a minimum, data concerning crash dynamics and airbag deployment criteria.
10. Future evaluations of the effectiveness of occupant protection features, such as restraint systems, airbags, and parachutes, would benefit from the establishment of a system to provide information about what aircraft safety equipment is installed on individual aircraft.

A complete discussion of these findings may be found in the NTSB report, but the analysis below will focus on the aspects of these and other accident investigations that can help to guide and inform biomechanics research.

IV. DISCUSSION

Real World Performance

In a GA aircraft airbag system, the trigger is a simple electromechanical device, in which a magnet pushes forward against a spring to close two open magnetic switches (Figure 2). As a result, the airbag system does not record any information regarding the crash pulse experienced at the sensor location. Given that an aviation crash frequently involves dramatically 3-dimensional impact accelerations, the lack of detailed accelerometer information is particularly limiting in calculating crash forces for aviation accidents. The estimation of crash forces was therefore often restricted in the NTSB study to simply identifying the direction of such forces from the primary impact. In current automotive airbag systems, the airbags are triggered by algorithms applied to data integrated and analyzed from high-frequency sampling of (often multiple) micro-electromechanical systems (MEMS) accelerometers. These data are typically fed into an event data recorder, the parameters of which are largely standardized in part as a response to an NTSB recommendation issued in 2004 [13], and from which valuable information regarding the crash can typically be derived. Given the plethora of multi-axis accelerometers in modern highway vehicles (the vast majority of which are now manufactured with some sort

of event data recorder on board [14]), it is sometimes hard to recall that real-world crash data from these devices have been available in any automobiles for less than two decades. The data that are currently derived from real-world crashes through the accelerometers and event data recorders in production automobiles are proving invaluable in identifying in detail the impact forces experienced in actual accidents [15]. The recording of these data in automobiles is now relatively routine, in large part driven initially by the needs of accident investigators, and the NTSB has recommended that the U.S. Federal Aviation Administration (FAA) consider requiring similar recording devices for aviation (Safety Recommendation A-11-5 in [5]).

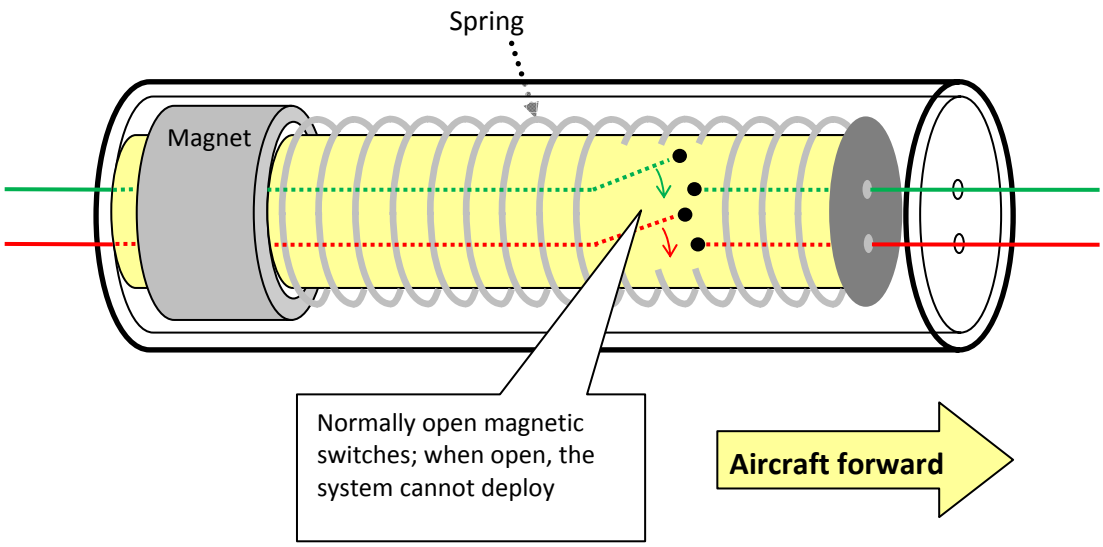

Fig. 2. Schematic of switch used to trigger general aviation airbag system

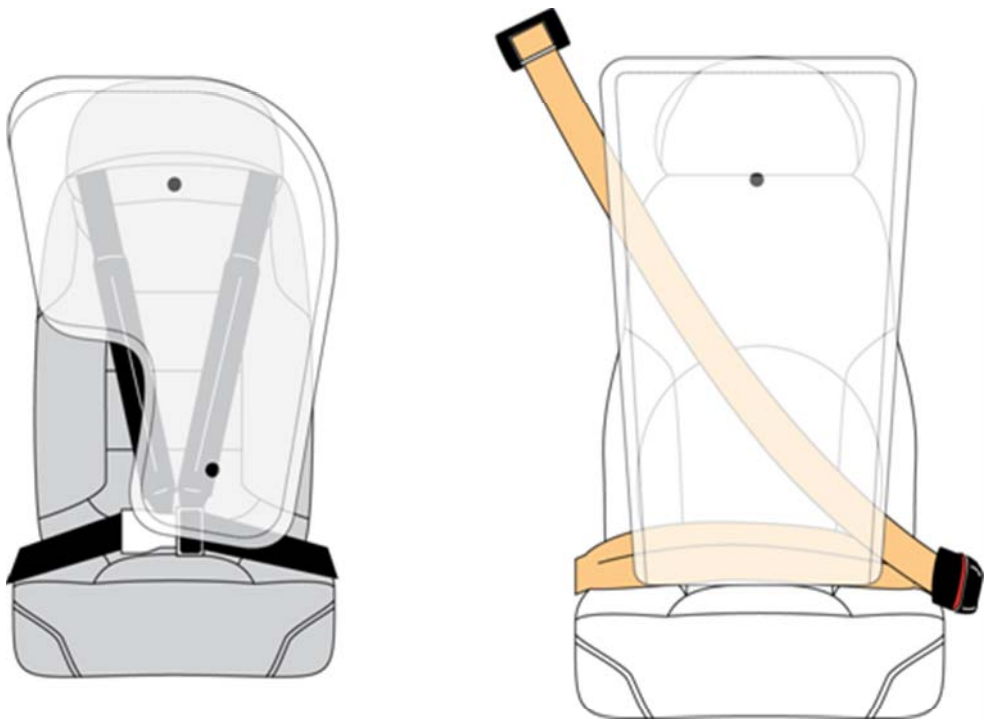

Fig. 3. Illustrations of left front seat occupant position restraint system in Cirrus (left) and Cessna (right) installations. An outline of the deployed airbag for each installation is overlaid in the nominal position for full deployment.

The NTSB GA airbag study included several markedly different aircraft types, and, though all airbags were

mounted in the restraint system, airbag positions varied both by position of occupant and by the type of aircraft. For example, Cirrus aircraft had the airbags mounted in the outboard (left or right, depending on seating position) shoulder harness of the 4-point restraint systems for the front seated occupants, while Cessna airbags were mounted in the lap portion of the 3-point restraints for front seated occupants (see figure 3). Thus the airbag deployment (and even the airbag shape) differed substantially between aircraft types. This variability, in combination with the relatively limited number of survivable accidents, and the complexity of the crash sequences, eliminated any possibility of epidemiological evaluation of the information gathered, and required investigators to evaluate each case independently for the types of information that might be useful in evaluating restraint system performance.

Unintended Consequences

Since September 1, 1997, all passenger cars sold in the United States have been required to be equipped with front position airbags subject to testing utilizing an unbelted dummy weighing 170 pounds in a 30 mile per hour crash test into a rigid barrier (later modified to include similar sled testing) [16]. Many manufacturers were meeting this standard well before that time, and, beginning in 1993, the U.S. National Highway Traffic Safety Administration (NHTSA) Special Crash Investigations program [17] and the NTSB [18] conducted investigations into automotive airbag performance and documented cases in which certain occupants, particularly children and infants, seated in the right front passenger seat had been killed by airbags in survivable low-speed crashes. Concern about airbag-induced fatalities led to a large-scale education campaign to educate caregivers about proper child seatbelt and safety seat use; it also prompted amendments to vehicle design regulations and the development of a new generation of “depowered” airbags to reduce the aggressivity of the bag [19]. More recent studies have demonstrated that the use of the depowered airbags has led to a significant reduction in risk of dying in frontal collisions among right front seat passengers under age 10, with no reduction in protection for other occupants [20].

Concern regarding the unintended consequences of airbag design and performance was one impetus for the NTSB GA airbag study. For each case, a team of investigators assessed the possibility that injury was caused or worsened by the presence of the airbag. In one case (Steamboat Springs, CO [21], as noted in [5]), a small adult passenger, 60 inches (152 cm) tall and 95 pounds (43 kg), in the right front seat of a Cirrus SR22 sustained injuries following a frontal impact and nose-over of the aircraft accompanied by airbag deployment. Her injuries included a chin abrasion, a bloody nose, a sprained left hand and wrist, and bruising near her 3rd and 4th ribs around the midpoint of her chest. She indicated that the chest bruise location was where the harness buckle of the 4-point restraint rested. A subsequent interview with the occupant confirmed that she typically adjusted the restraint so that the buckle rested at the base of her sternum (rather than at the center of the pelvis, as intended by the design of the restraint system). Her facial injuries were determined by the NTSB to have likely been caused by direct contact of the airbag with her face during the airbag deployment. Her improper use of the restraint system, which positioned the buckle too high on her chest, may have contributed to these injuries because the occupant’s face would have been in closer proximity to the shoulder harness-mounted airbag at initial deployment. Though there were no other cases in which injury was determined to have been related to the airbag deployment, this case served to illustrate certain concerns regarding the potential for such injury, in addition to the issue of misuse of 4-point restraint systems, discussed below.

Actual Use

Multiple studies over many years have identified common patterns of misuse of automobile child restraint systems across a variety of populations [22],[23],[24], and a great deal of work on design [25] and education [26] has taken place in an attempt to make such misuse less likely. No similar studies have looked at the issue of restraint misuse in GA aircraft, but the NTSB GA airbag study allowed a glimpse into some concerning and potentially common patterns of misuse of restraint systems in the accidents evaluated.

In the Cirrus SR22 accident noted above, not only the right front seat passenger (a physician), but also two adolescents in the back seats of the aircraft had made the same error of use of the 4-point system. When unbuckled and not in use, the 4-point restraint systems on the Cirrus SR22 appear as shown in figure 4. The buckle portion rests at the midpoint of the seatback, because when the restraints are unfastened, the inertial reel retracts and takes up the slack in the shoulder harness portion of the restraint. Because of the inertial reel

system, the restraints feel snug after the buckle is fastened, and the restraint as thus arranged is not entirely unlike a backpack harness, with which many occupants may be more familiar than a four-point restraint. In the Steamboat Springs accident, three of the four occupants appear to have misused the restraint with the lap buckle at chest level. The Pilot's Operating Handbook for the aircraft notes that, after fastening the buckle, it is necessary to pull on the seat belt tabs to center and tighten the buckle over the hips for maximum comfort and safety, an action that was apparently not intuitive to the passengers in this accident.

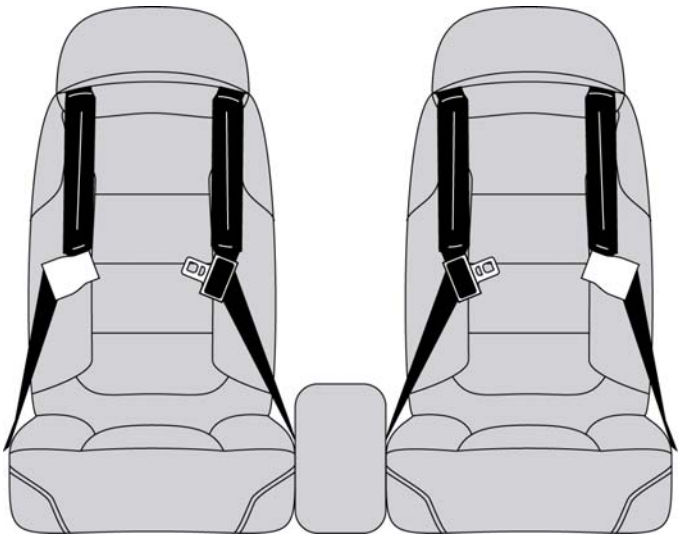

Fig. 4. Illustration of the position of the 4-point restraint systems in the Cirrus SR22 when the buckles are unfastened.

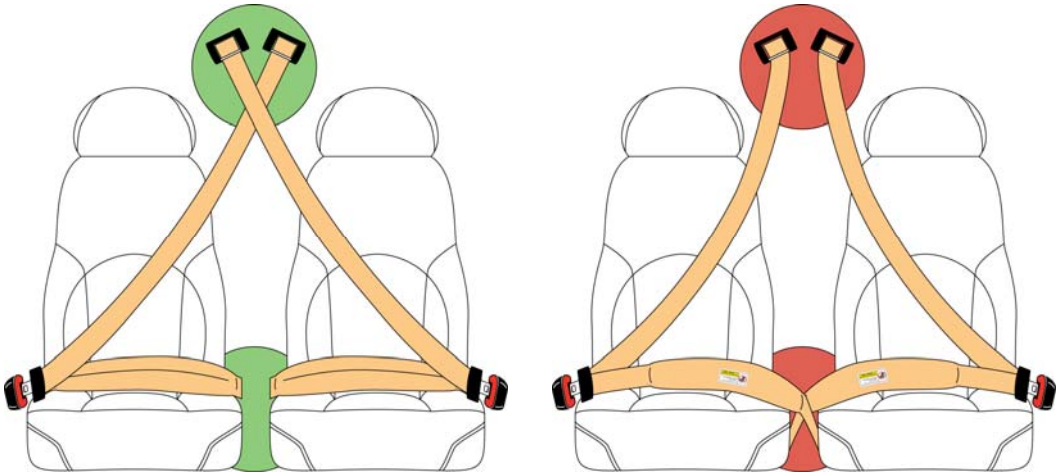

Fig. 5. Illustrations of the correct (left) and incorrect (right) latch configurations for the pilot and front passenger seats of a Cessna 172S.

In the investigation of a Cessna 182 accident in Athens, TX ([27], as noted in [5]), the NTSB study identified a second potential pattern of misuse, during an interview in which the pilot, a certified flight instructor, had noted numerous circumstances (including at the beginning of the accident flight) of passengers or students in the front seat attempting to use the three-point restraint intended for the occupant in the opposite-side seat. This can occur because both restraints hang from the upper attachment points close to one another, and the restraint for the seat occupant is actually the one furthest away, so that in correct usage, the restraints for the left and right front seat occupant are crossed, which may be counterintuitive to occupants. The use of the incorrect restraint system has significant implications, in that the buckle must be used in order to activate the airbag system, and when the incorrect restraint is inserted into the buckle, it is the opposite restraint airbag system that is activated (Figure 5). Occupants may therefore not benefit from the airbag system when the restraints are misused in this way.

The NTSB recommended that the FAA revise the guidance and certification standards concerning restraint

systems to recognize and prevent potential misuse scenarios, and to require design changes to eliminate the possibility of misuse that would inadvertently inactivate the airbag system (Safety Recommendations A-11-1 and A-11-2 in [5]).

Population Variation

In the introduction to the special conditions set by the FAA for the certification for airbag-equipped restraints in aircraft, the following is noted: "It is possible a wide range of occupants will use the inflatable restraint. Thus, the protection offered by this restraint should be effective for occupants that range from the fifth percentile female to the ninety-fifth percentile male" [28]. No information is provided to explain how the restraint effectiveness should be evaluated for the range of occupants noted, and the range itself is not specifically defined. Emergency landing conditions testing required by the FAA [29] refers only to a NHTSA- or FAA-approved anthropomorphic test dummy with a nominal weight of about 170 pounds (77 kg). The average age of the GA accident-involved pilot in 2005 was 50 [30]: the 95th percentile weight for 50- to 59-year-old males in the United States around that time was 260 pounds (118 kg), and the 95th percentile waist circumference for that same group was 51 inches (130 cm) [31]. It is unclear whether the airbag-equipped restraints were designed or tested with this population in mind.

In a Cessna 172 accident in Fullerton, CA ([32], as noted in [5]), the NTSB noted that the pilot's above average waist size resulted in the lap-belt mounted airbag being initially positioned off to the pilot's right side (see figure 6) and that the airbag's interaction with his right arm may have prevented the airbag from fully deploying toward his head, thereby reducing its effectiveness for head protection. The pilot in this case was 71 inches (180 cm) tall and weighed 245 pounds (111 kg), for a body mass index (BMI) of 34.2. Of the 23 adult occupants in the accidents investigated for the study, 5 were obese (body mass index > 30) and 5 more were overweight (body mass index > 25). In several cases involving overweight or obese occupants, egress from inverted airplanes was reported to be problematic, potentially due to the additional weight being placed on the restraints by the occupants' bodies and/or difficulty reaching the buckle located near the occupant's hip. On the opposite side of the spectrum, as noted above for the small females in the Steamboat Springs, CO accident, restraint use may present different problems.

Fig. 6. Diagram showing how a lap belt mounted airbag would be shifted to one side when used by an obese occupant.

Based on accident investigation findings of restraint concerns within the anthropometric range of the intended user population, the NTSB recommended that the FAA modify the special conditions for the installation of inflatable restraints on GA airplanes to provide specific guidance to manufacturers as to how they should demonstrate that the protection is effective for occupants that range from the 5th percentile female to the 95th percentile male (Safety Recommendation A-11-3 in [5]).

Other Issues

The investigation of accidents, particularly those involving injury or fatality, often serves to focus public attention on a subject. The investigations in the 1990s noted above, of accidents in which children and infants in the front seat had been killed by airbags in survivable low-speed crashes, were considerably more effective in stimulating action by regulators and others than the identification decades earlier by biomechanics researchers of the potential for such interactions [33]. Accidents are also commonly investigated for legal reasons, both

criminal and civil. The design and positioning of gasoline tanks in small cars will be lastingly influenced by legal actions and decisions arising from the litigation of several fatal accidents involving the Ford Pinto in the 1970s [34]. Finally, the advent of new technologies is making the investigation of accidents more comprehensive and permitting the collection of biomechanical data on individual accident cases that had previously been available only in the laboratory. MEMS accelerometers, noted above, are not only sampled for vehicle data, but in IndyCar races, such accelerometers are required equipment in the earpiece of the driver (see figure 7), yielding extraordinarily detailed data on the accelerations experienced by the head of the driver; and assuming that there is a U.S. National Football League season in 2011, the league may include accelerometers in some players' helmets and mouthpieces [35].

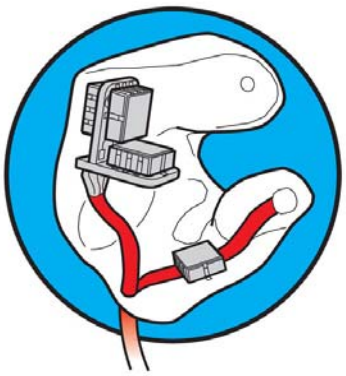

Fig. 7. Diagram of earpiece-mounted accelerometers required for use by all IndyCar drivers (courtesy of IndyCar, LLC, used with permission).

V. CONCLUSIONS

No lives were ever saved or injuries mitigated by an accident investigation or by a laboratory data set. It is only when findings from these sources are incorporated into the design of roadways, vehicles, restraints, monitoring systems, and other factors that accidents are prevented, impact forces attenuated, or survival enhanced.

Accident investigation often serves to help focus biomechanics research. First and foremost, transportation biomechanics research is for the protection of the traveling population, and for this group, it is critical that the findings result in interventions that are either transparent to the end user or uncomplicated to use (and hard to misuse). Regulators, who must use biomechanics principles to arrive at enforceable performance standards for vehicles and equipment, generally prefer simplicity over complexity. Vehicle and equipment designers look for biomechanics information that will allow a certain elegance of design in the integration of safety features. Manufacturers are often required to consider cost and marketing potential along with effectiveness when evaluating research to improve safety performance. Legislative bodies may not always understand the intricacies of biomechanical principles, but they will be quick to seize on examples of public concern. Biomechanics researchers and accident investigators (who, after all, are not always different people) must navigate the often competing priorities of various groups and organizations in ensuring that the best science is being utilized in the most effective manner to protect vehicle occupants now and in the future.

VI. ACKNOWLEDGEMENT

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