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AN UNDER-HAND STEERING WHEEL GRASP PRODUCES SIGNIFICANT INJURY RISK TO THE UPPER EXTREMITY DURING AIRBAG DEPLOYMENT

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ABSTRACT

Recent laboratory investigations suggest that a deploying airbag may fracture the forearm. These studies positioned the arm in an overhand grasp placing the forearm over the airbag module. However, there is little published data on how drivers grip the steering wheel and the general proximity of the upper extremity to the airbag module. The objective of the current study was to identify 'real world' upper extremity positions and to correlate these with accident and experimental data. A survey of the National Automotive Sampling System (NASS) for the years 1995-99 revealed an increase in the number of forearm fractures due to driver-airbag interaction. As NASS does not provide the position of the forearm, common upper extremity positions were identified in a volunteer driving population. These positions were simulated using a specially instrumented 50th percentile male dummy to determine the relative injury risk for the different positions. Analysis showed that an under hand grasp of the wheel turned 90° yielded the highest magnitude impact event. This single position was then simulated in 9 cadaver experiments. Dual stage airbag deployments produced forearm fractures in 2 arms. Experiments using the contralateral arms from the fractured subjects with a single stage airbag deployment produced no fractures. Analysis of forearm kinematics suggests that increasing forearm velocity and thus, acceleration exposure, is associated with forearm injury. Further, the data suggests that

reductions in acceleration exposure via reduced airbag inflation decreased the apparent risk of forearm fracture.

The effectiveness of the airbag restraint systems in reducing automotive fatalities has been well documented (1,2). It is estimated that while safety belts are ~42% more effective in preventing fatalities; the addition of the driver side airbag provides a ~12% increase in effectiveness in reducing fatalities in crashes. But despite the effectiveness of airbag systems, there is evidence of increased risk of non-fatal injuries (2-13). For example, a field study conducted by Huelke et al., (14), has revealed two likely forearm injury modalities associated with airbag deploys: 'flinging' and 'primary contact'. The primary contact modality was associated with more serious fractures and joint dislocations. The most frequently injured anatomical structure was the forearm involving bone fracture of the distal region. The injury mechanism is likely due to the inertial resistance of the arm's mass and may be a consequence of direct impact loading or 3-point bending as the forearm is loaded at the mid-shaft.

Taylor, et al., (15) studied the NASS for the years 1988-94 and found that 1% of the drivers, restrained only by seatbelts, sustained upper extremity injury, while 4.4 % of drivers, restrained by both seatbelts and airbag systems had such injury. When restricting the analysis to those cases in which a bag deployed and there was an upper extremity injury, the injury severities were generally AIS ≥ 2 and were associated with a relatively low ΔV (<15mph). Taylor et al., also indicate that women are more susceptible to upper extremity injuries from deploying airbags, perhaps due to variations in bone quality, and their decreased stature. This latter observation leads to closer proximity to the airbag module, suggesting that airbag-upper extremity positioning may be an important factor.

These data helped form the basis of additional studies (15-17) assessing the potential of forearm fracture due to a deploying driver airbag. These experimental investigations all employed a similar forearm-airbag positioning methodology: overhand grasp of the top of steering wheel with an instrumented dummy forearm positioned over the airbag module with the wheel rotated to different positions leading to variations in the location of the tear seam relative to the forearm. This 'worst case' position was based on several factors. First, testing indicated that bending moments were maximized when the forearm was oriented perpendicular to the airbag tear seam, and reduced as it moved away from the module. Secondly, the distal third of the forearm is the weakest location in bending. Finally, the

orientation of humerus normal to the steering wheel forces the center of rotation of the forearm to be approximately about the elbow. Hardy et al, (17) studied effect of proximity on instrumented cadaver forearms positioned over deploying airbags with the steering wheel in neutral position. They concluded that the risk of forearm fracture increases with increasing proximity of the forearm and airbag module. They further noted the very strong, positive correlation between distal forearm speed and fracture occurrence.

While these previous studies provide valuable data on the risk of forearm injury, only a limited number of forearm positions were studied. Since these studies were based on an overhand grasp of the steering wheel, the forearm acceleration magnitudes were mainly a function of the inertial resistance of the forearm. We are unaware of a driver upper extremity positioning study of seated drivers examining forearm positioning and the relative risks of these positions.

In the current study, we hypothesized that a deploying airbag can subject the forearm to varying degrees of primary contact injury risk based on forearm positioning and that this risk would be correlated with forearm kinematics. To address this hypothesis we developed the following objectives: 1) identify the risk of upper extremity injury concomitant with airbag deployment in government accident statistics, 2) examine driver upper extremity positioning while driving straight and executing turns to assess the proximity of the forearm to the airbag, 3) analyze the relative injury risk of different forearm positions, using a specially instrumented anthropomorphic test dummy, and 4) test in replication the position from the dummy tests which represented the greatest magnitude of upper extremity loading using human cadavers to assess the risk of forearm injury using single and dual stage airbags.

METHODS AND MATERIALS

Analysis of Accident Statistics: The NASS/CDS (National Automotive Sampling System/Crashworthiness Data System) were analyzed for upper extremity injuries for the years 1979 through 1999 inclusive, with more detailed analysis for 1995-99. The longer period provided insight into the time period spanning the pre-airbag and airbag fitted fleet while the latter time interval is designed to assess the greater concentration of airbag equipped vehicles. The main aim of the NASS data analysis was as follows: 1) to determine the frequency of upper extremity injuries 2) the type of forearm injuries suffered by the driver, and 3) to associate different injury modalities with their causes. The data was analyzed for the following information: the gender of the occupant, type and usage of restraints (airbags, seatbelts), and the specific type of injuries.

Driver Upper Extremity positioning study: Thirty adult drivers (18+ years old) were recruited for the upper extremity positioning

study with the following approximate anthropometry: ten 5th percentile females (152-157 cm), ten 50th percentile males (175-180 cm) and ten 95th percentile males (188-193 cm). The survey population was comprised of faculty, staff, and students from the Kettering University community. The drivers were asked to sit in the driver's seat of a consistent passenger car environment. To limit subject bias, the drivers were informed that the investigators were studying seat belt comfort in different driving positions. The drivers were asked to simulate driving straight, turning the wheel 90° clockwise (CW) and 90° counter-clockwise (CCW) from the neutral position. The following data were recorded: seat track position, hand positions on steering wheel, driver height and the distance between: the elbow and wrist, elbow and shoulder, and shoulder and steering wheel. The position of the hands on the steering wheel was documented using radial clock positions, i.e., grasping the wheel at the top in the neutral position was assigned a 12 o'clock value. By maintaining this attachment to the steering wheel and rotating it 90° (right or left), a value of 12 o'clock was still associated with this position. A one-way ANOVA with S-N-K post-hoc testing was used to detect differences in subject anthropometrical measurements and hand placements ($p=0.05$).

Anthropomorphic Dummy Tests: A series of 7 static dual stage airbag deployment tests were conducted on a 50th percentile male dummy, with an instrumented left arm, to determine the most severe of 7 candidate positions (Figure 1 A-G), from the driver upper extremity positioning study. Five of the positions represented close proximity or 'test' positions of the forearm-airbag module, while two positions placed the forearm remote to the airbag module and were considered 'control' positions. The test buck was fitted with an exemplar steering column, adjustable steering wheel, and adjustable seats. Both stages of the dual stage airbag were deployed for all tests. The instrumentation included triaxial accelerometers at the distal and proximal left forearm as well as the distal and proximal left humerus. A wrist load cell was incorporated to record loading axial to the forearm. All data was filtered using CFC 180 (16) per SAE J211. Two high speed (2250 Hz) camera views (over-the-shoulder and lateral) were used to document the deployment event. The camera image acquisition was synchronized to the data acquisition from the arm. Pressure sensitive film (Fuji Ultra Super Low: range = 0.05 – 1.00 MPa) was wrapped around the forearm to transduce the magnitude and distribution of contact pressure. The film was encased in a polyethylene packet to reduce shear-loading artifact. The fingers of the dummy were lightly held on the steering wheel using adhesive tape, to simulate the fingers grasping the wheel. This methodology was based on Hardy, et al., (17) who show that grip force has negligible contribution to the overall upper extremity kinematics. As

a measure of acceleration exposure, the resultant acceleration was averaged over the duration of primary contact time (primary contact time is defined as the time interval between initial airbag-forearm contact and complete release of the hand from the steering wheel). The average acceleration data points for each of the 10 tests were plotted against the primary contact time. Analysis of the wrist acceleration, velocity, contact pressure and area, and wrist loading data from these tests yielded the highest accelerations, wrist loading, and contact pressures and were thus retested to validate the initial findings.

Cadaver Tests: 9 unembalmed human upper extremities (6 left arms, and 3 right arms from 6 cadavers, Table 1) were used to

Table 1: Cadaver characteristics.

| Cadaver | Age | Sex | Height (cm) | Mass (kgs) | Limb tested | Cause of Death |
|---------|-----|-----|-------------|------------|-------------|----------------|
| 1 | 75 | M | 175 | 84.5 | L | MI |
| 2 | 81 | M | 168.8 | 69.5 | L | CVA |
| 3 | 80 | M | 175.5 | 51.6 | L | Pneumonia |
| 4 | 75 | M | 178.7 | 86.4 | R and L | CVA |
| 5 | 88 | F | 168.5 | 63.0 | R and L | MI |
| 6 | 91 | M | 166.2 | 55 | R and L | CVA |

investigate the risk of upper-extremity injuries resulting from direct interaction with a driver airbag. All arms were positioned in the position identified in the dummy tests which subjected the forearm to the collective greatest accelerations, wrist loads, and contact



Figure A: Position A, Single overhand grasp at 12 o'clock, steering wheel neutral

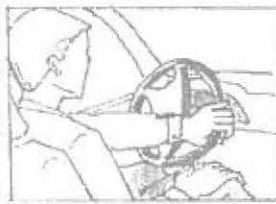


Figure B: Position B, Single overhand grasp at 9 o'clock, steering wheel turned 90° CW.

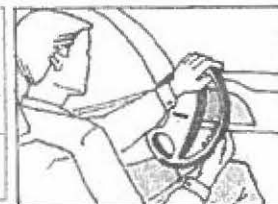


Figure C: Position C, Single overhand grasp at 9 o'clock, steering wheel turned 90° CW.



Figure D: Position D, Single underhand grasp at 10 o'clock, steering wheel turned 90° CW.

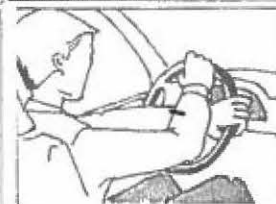


Figure E: Position E, Both-hand grasp at 12 and 9 o'clock, steering wheel turned 90° CW.

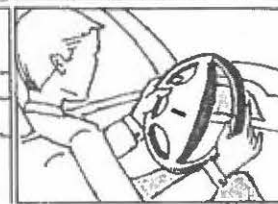


Figure F: Position F, Both-hand grasp at 7 and 12 o'clock, steering wheel turned 90° CW.



Figure G: Position G, Single hand grasp at 9 o'clock, steering wheel neutral.

Figure 1 (A-G): Driver upper extremity-airbag module positions observed in the current study. The airbag tear seam is indicated by the dark bar indicating its orientation of the forearm.

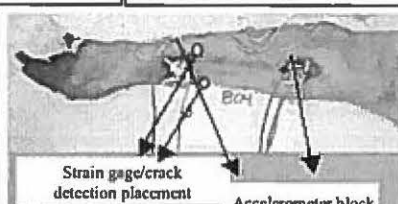


Figure 2: Transducer positioning.

pressures: an underhand grasp with the wheel turned 90° away from the limb being tested (Figure 1 D: shown with left arm). The testing was conducted in two phases: 1) all 6 left arms were tested using a dual stage airbag and 2) three contralateral arms (Table 1) were tested with only the primary stage of the airbag being deployed. The cadaver arms were instrumented with a triaxial accelerometer rigidly attached to the distal radius via a steel-mounting block (Figure 2). Access to the radius was achieved via a modified volar (anterior) approach, which longitudinally separated the forearm musculature. A mounting block was attached to the bone via stiff plastic straps wrapped around the bone and the accelerometers were subsequently attached to the blocks using screws. Strain gages were also affixed to the shaft of the distal third radius and ulna (positioned to record axial surface strains). They were used to record the strain history associated with the airbag deployment to help elucidate the timing of forearm skeletal loading. All data was filtered using CFC 180. In two subjects from the dual stage experiments crack detection gages were also fitted to the radius and ulna, proximal to the strain gages. Forearm-airbag contact pressures were recorded using the same method applied during the dummy tests. Post-test analysis included X-ray and autopsy of the extremities to identify fracture occurrence. The resultant acceleration was averaged over the duration of primary contact time for each cadaver test, as a measure of acceleration exposure. This data was plotted against the primary contact time.

RESULTS

Analysis of Accident Statistics: The NASS study revealed that upper extremity (shoulder, arm, elbow, forearm, wrist and whole extremity) injuries consistently account for approximately 18% of the injuries in NASS each year (Figure 3). Overall the vast majority of

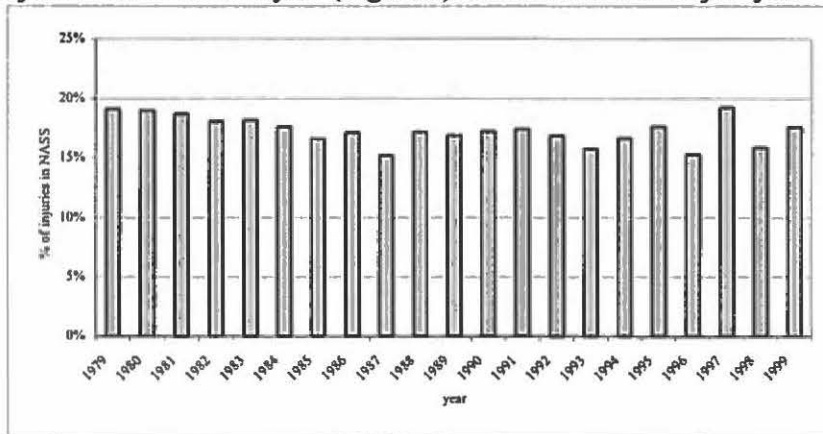


Figure 3: Upper extremity injuries presented as the ratio of all upper extremity injuries to all injuries in NASS.

injuries caused by airbags were minor (Figure 4) and were rated AIS 1 (~95%), with approximately 4% scoring AIS 2 and the balance (~1%) scoring AIS 3. In frontal crashes with ΔV from 15 to 35 mph

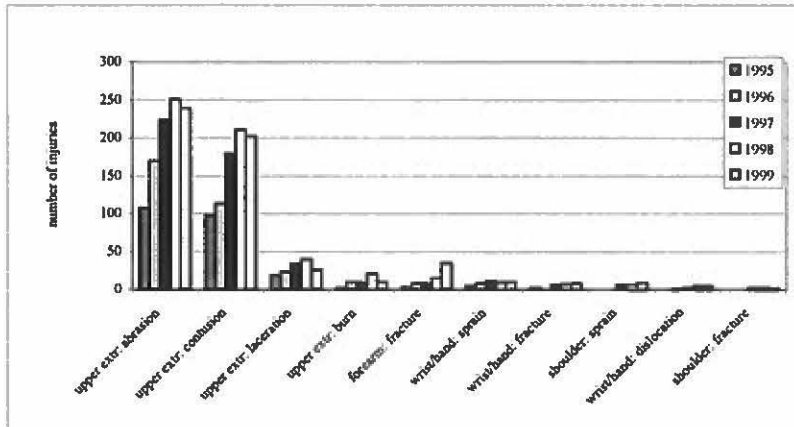


Figure 4: Top 10 upper extremity injuries from a driver's airbag.

the deployment of an air bag reduced the severity of upper extremity injury. The proportion of minor injuries (AIS 1) is higher when a bag deploys (90% of bag deployment injuries) than when there is no deployment (80% when no bag available). Restraint use did not influence the location of upper extremity injury and in cases where the driver airbag deployed; restraint use did not alter the AIS level of the injury. Similar to previous studies, it was found that women were at an increased risk for injury, with approximately 30% of female drivers injured by an airbag deployment versus 20% of male drivers (Figure 5). The majority of serious (AIS 3+) upper extremity

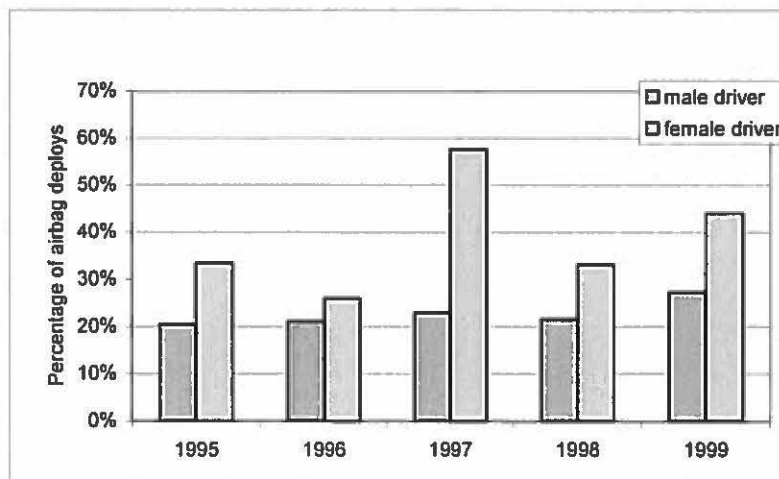


Figure 5: Proportion of deployments for male/female drivers concomitant with upper extremity injury (soft tissue and bone injuries).

injuries attributed to the driver airbag were forearm fractures (39 of 42 injuries for 1995-1999). The airbag cover was frequently cited as the injury source in these cases, suggesting proximity to the airbag increases the likelihood of serious upper extremity injury. The vast majority of forearm fractures involved a single limb.

Driver Upper Extremity Positioning Study: An analysis of data and images collected from the driver upper extremity positioning study revealed 5 positions in which the forearm was in close proximity to the airbag module (Figure 1). These positions included 3 single over-hand grasps of the top of the steering wheel (Figures 1 A-C), an underhand grasp of the top of the steering wheel (Figure 1 D), and one double, crossed-over hand grasp (Figure 1 E). Two additional positions (Figures 1 F-G), which were remote to the steering wheel, were also considered as a control. For the 9 subject-positions studied (3 anthropometries by 3 driving positions), the underhand grasp represented 8% of all positions. This biased somewhat in the observation that an underhand grasp was never used due to its likely awkward position. Thus, when only considering turning the wheel right or left, the underhand grasp represented 12% of all positions. Analysis of the volunteer positioning suggested that forearm placement was not necessarily a function of anthropometry. For example, the underhand grasp was used by a combined 17% of subjects represented by two females (5th percentile) and three males (two 50th percentile, and one 95th percentile) (Table 2). Numerous

Table 2: Hand position characteristics.

| Stature based Anthropometry | Driving straight | Turning left | Turning right |
|-----------------------------|---|---|--|
| 5 th , Female | All over hand grasps 7 using Left and Right 1 using Left only 2 using Right only | 8 over hand grasps 2 under hand grasps 9 using Left and Right 1 using Right only | 8 over hand grasps 2 under hand grasps 8 using Left and Right 1 using Left only 1 using Right only |
| 50 th , Male | All over hand grasps 7 using Left and Right 3 using Left only | All over hand grasps 6 using Left and Right 3 using Left only 1 using Right only | 8 over hand grasps 2 under hand grasps 6 using Left and Right 1 using Left only 3 using Right only |
| 95 th , Male | All over hand grasps 1 using Left and Right 8 using Left only 1 using Right only | 9 over hand grasps 1 under hand grasp 5 using Left and Right 3 using Left only 2 using Right only | All over hand grasps 3 using Left and Right 5 using Left only 2 using Right only |

Table 3: Comparison of statistics of the recruited drivers (all dimensions are in meters).

| Stature based Anthropometry | Height | Shoulder to Elbow | Elbow to Wrist | Shoulder to steering wheel | Seat track position |
|-----------------------------|------------|-------------------|----------------|----------------------------|---------------------|
| 5 th , Female | 1.56±0.02 | 0.27±0.03 | 0.23±0.014 | 0.48±0.026 | 0.086±0.04 |
| 50 th , Male | 1.77±0.015 | 0.28±0.014 | 0.27±0.016 | 0.57±0.025 | 0.16±0.029 |
| 95 th , Male | 1.91±0.037 | 0.32±0.023 | 0.29±0.018 | 0.62±0.028 | 0.22±0.017 |

Table 4: Comparison of hand positions on the steering wheel (refer to text for clock position definition).

| Steering wheel positions | 5 th , Female | | 50 th , Male | | 95 th , Male | |
|--------------------------|--------------------------|-------------|-------------------------|-------------|-------------------------|-------------|
| | Left Hand | Right Hand | Left Hand | Right Hand | Left Hand | Right Hand |
| Driving straight (9) | 9.38 ± 1.38 | 4.17 ± 4 | 9.78 ± 2.03 | 4.43 ± 3.44 | 9.11 ± 1.96 | 3 ± 0 |
| Turning Left (8) | 9.75 ± 2.85 | 4.43 ± 4.45 | 10.61 ± 1.02 | 4.5 ± 4.06 | 10.19 ± 3.2 | 5.93 ± 4.26 |
| Turning Right (4) | 10.12 ± 2.38 | 5.44 ± 4.9 | 10.08 ± 2 | 6.85 ± 5.18 | 9.24 ± 2.46 | 7.8 ± 4.55 |

drivers in all anthropometries used a single overhand grasp of the top of the steering wheel. An increase in driver height resulted in an increase in arm positioning relative to the steering wheel and seat track position (Table 3). The vast majority of recruited drivers grasped the steering wheel with a single hand (the left) (Table 4) at

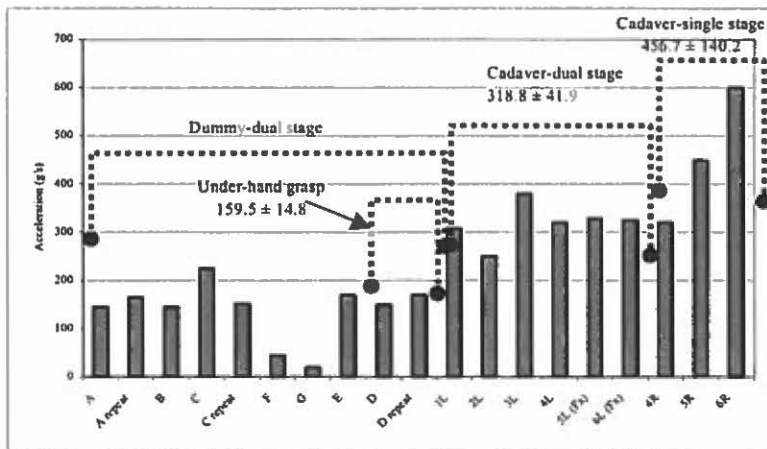


Figure 6: Peak wrist resultant accelerations in G's (CFC 180).

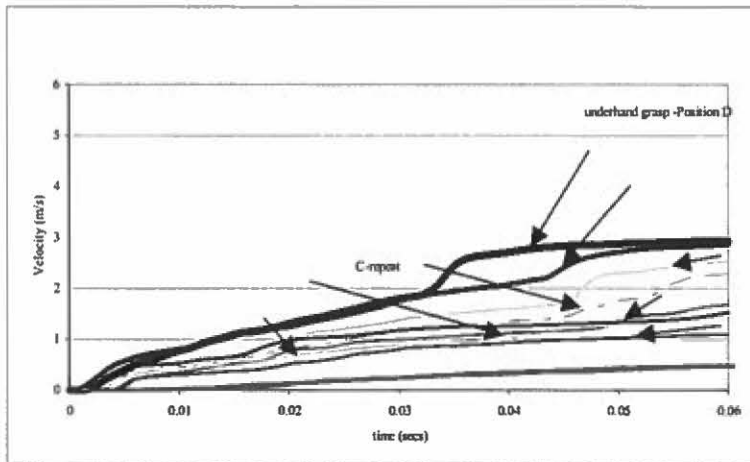


Figure 7: Velocity plots for dummy testing (refer table 5, figure 1, for details regarding arm positioning).

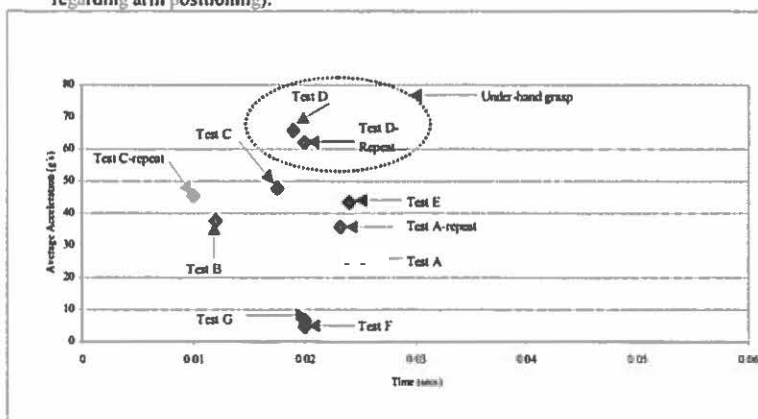
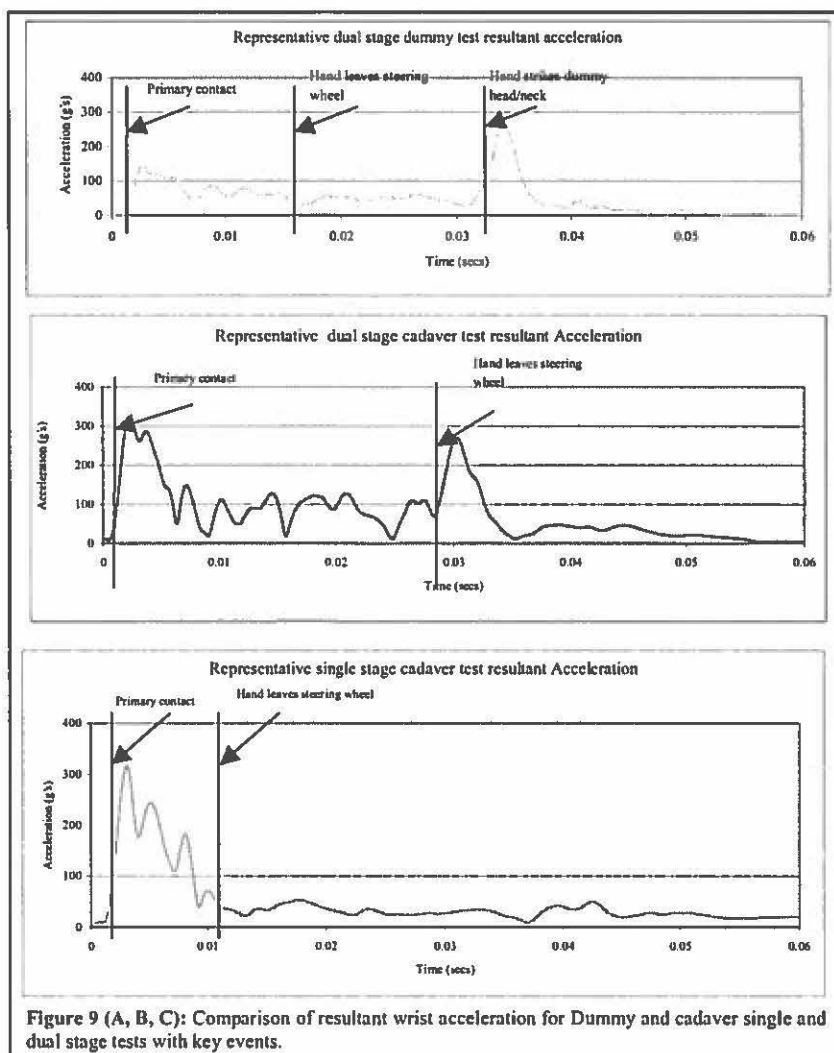


Figure 8: Average acceleration vs. primary contact duration of contact for dual stage dummy tests.

the 10 o'clock position while simulating the neutral, turning left, and turning right positions (Figures 1, Table 4). The non-usage of either

the left or right hand to grasp the steering wheel was considered a blank in the spreadsheet. If the right hand was used it was typically placed at the 4-6 o'clock position. Interestingly, the usage of both the left and right hands on the steering wheel varied with stature (Table 2). For example, the use of both hands was more frequent among female drivers (5th percentile volunteers), while virtually all large male drivers (95th percentile) used a single hand.

Anthropomorphic Dummy Tests: An analysis of the dual stage deployment experiments showed a wide variation in forearm kinematics and contact mechanics as the forearm position was varied relative to the deploying airbag. For all tests, the peak wrist resultant accelerations varied from 20-230 g's (Figure 6) while the velocities



varied from 0.5-3 m/s (Figure 7). The peak proximal forearm and humeral accelerations were negligible and were not considered for further analysis. The rotation of forearm about the elbow resulted in

considerably lower proximal forearm acceleration values. While position C (Figure 1, overhand grasp at 9 o'clock, turning right) produced the greatest primary (airbag-arm contact as opposed to flinging) peak acceleration, the underhand grasp had the greatest velocity-time profile of all positions tested. Analysis of the average and peak contact pressure and contact area data also showed that the underhand grasp position represented the most consistent, elevated values (average: 0.44 ± 0.08 MPa, peak: 1.05 ± 0.14 MPa). Analysis of the acceleration-time history and high speed video images for the underhand grasp showed peak, primary contact at 2 ms (Figure 9A), the wrist hyper extending and leaving the steering wheel at approximately 18 ms, and the hand striking the dummy neck or thorax at 35-45 ms (time zero for all kinematic-time histories was synchronized to initial failure of the tear seam - Table 5). Moreover,

Table 5: Chronological sequence of events occurring in dual stage/single stage airbag dummy/cadaver tests (time zero for all the tests was considered as airbag break through).

| Test Number | Major events occurring | Time of occurrence (secs) |
|---|--------------------------------|---------------------------|
| A and A repeat | Airbag hits forearm | 0.003 ± 0.0 |
| | Hand leaves the steering wheel | 0.0235 ± 0.05 |
| B | Airbag hits forearm | 0.003 |
| | Hand leaves the steering wheel | 0.012 |
| C and C repeat | Airbag hits forearm | 0.003 ± 0.0 |
| | Hand leaves the steering wheel | 0.0135 ± 0.04 |
| F | Airbag hits forearm | 0.005 |
| | Hand leaves the steering wheel | 0.015 |
| G | Airbag hits forearm | 0.005 |
| | Hand leaves the steering wheel | 0.018 |
| E | Airbag hits forearm | 0.002 |
| | Hand leaves the steering wheel | 0.024 |
| D and D repeat | Airbag hits forearm | 0.001 ± 0.0 |
| | Hand leaves the steering wheel | 0.018 ± 0.02 |
| Dual stage cadaver testing (n=6, 1L-6L) | Airbag hits forearm | 0.001 ± 0.0 |
| | Hand leaves the steering wheel | 0.040 ± 0.007 |
| Single stage cadaver testing (n=3, 4R-6R) | Airbag hits forearm | 0.001 ± 0.0 |
| | Hand leaves the steering wheel | 0.0126 ± 0.005 |

a plot of average acceleration exposure vs. primary contact time revealed that the underhand grasp (test D, Figure 1D) had the greatest average acceleration (Figure 8). Finally, the peak wrist loading axial

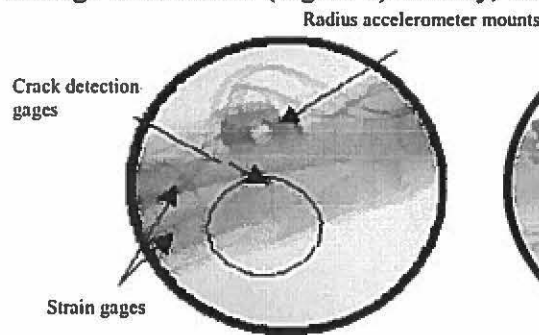


Figure 10: Displaced transverse ulnar fracture produced by a dual stage

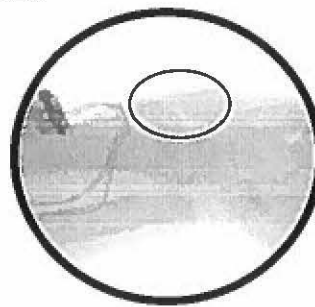


Figure 11: Non-displaced radius fracture at the styloid process produced by a dual stage deployment of the underhand grasp.

to the forearm was approximately 750 N for the underhand grasp, which was higher than any other position.

Cadaver Tests: Similar kinematics were noted in the dual stage deployment phase of cadaver testing as in the dummy testing. Post-

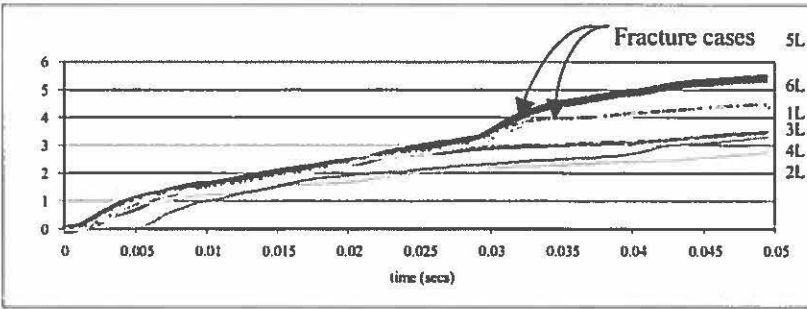


Figure 12: Wrist resultant velocities (m/s) versus time (s) for dual stage airbag cadaver testing – underhand grasp.

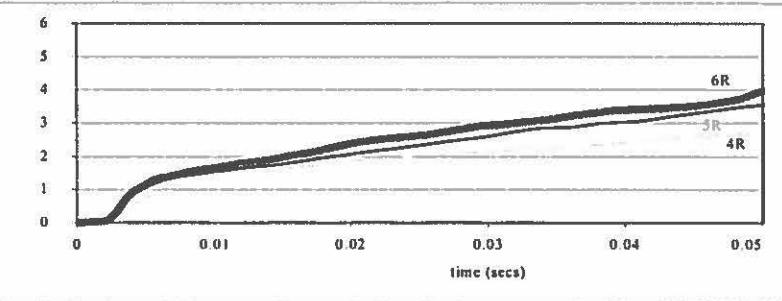


Figure 13: Wrist resultant velocities (m/s) versus time (s) for single stage airbag cadaver testing – underhand grasp.

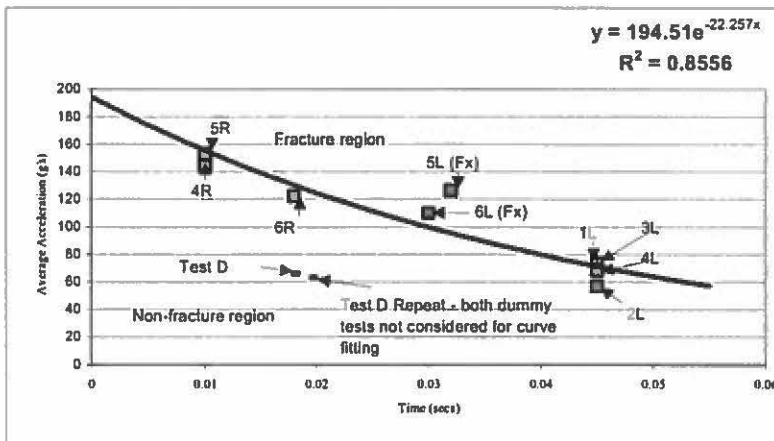


Figure 14: A comparison of average acceleration vs. primary contact time (see text for definition of primary contact) values from the single/dual stage cadaver tests (tests 1-6 for right and left) and the dual stage dummy tests (test D). All datapoints represent the underhand grasp position (all for the underhand grasp).

test autopsy showed that one of the forearms suffered a displaced ulna shaft fracture (AIS 3) (Figure 10), and the other, a non-displaced radius styloid fracture (AIS 2) (Figure 11). No injury was detected in any of the other dual stage experiments or any of the single stage deployment experiments. The peak wrist resultant accelerations averaged 318 ± 41.9 g's for the dual stage experiments and 456 ± 140.2 g's for the single stage experiments (Figure 6). The velocity-time histories of the dual stage experiments (3-5.5 m/s) (Figure 12) were higher than the single stage experiments (3-4 m/s) (Figure 13)

indicating a longer and more intense acceleration exposure for the dual versus the single stage experiments. The greatest dual stage velocities were associated with the fractured specimens (subjects 5L and 6L). The acceleration time histories for the non-fracture, single and dual stage experiments consistently showed a single peak of acceleration during primary contact (0-10 ms with time zero again referenced to initial failure of the tear seam) (Figure 9C). Conversely, the fractured, dual stage experiments exhibited a dual peak acceleration profile: one peak during primary contact (0-10 ms) and a second as the hand released from the wheel (Figure 9B). Interestingly, the plot of average acceleration exposure vs. primary contact time revealed that the fracture cases had the greatest acceleration exposure (Figure 14).

There was an unexpected similarity between the sequence and timing of events between the dual stage dummy experiments and single stage cadaver experiments. Specific to both of these cases,

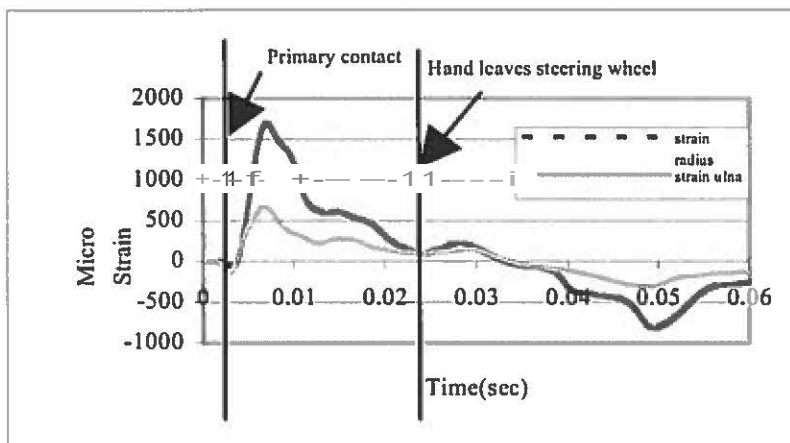


Figure 15: Distal forearm axial strain gage history (cadaver 6R-Single stage deployment).

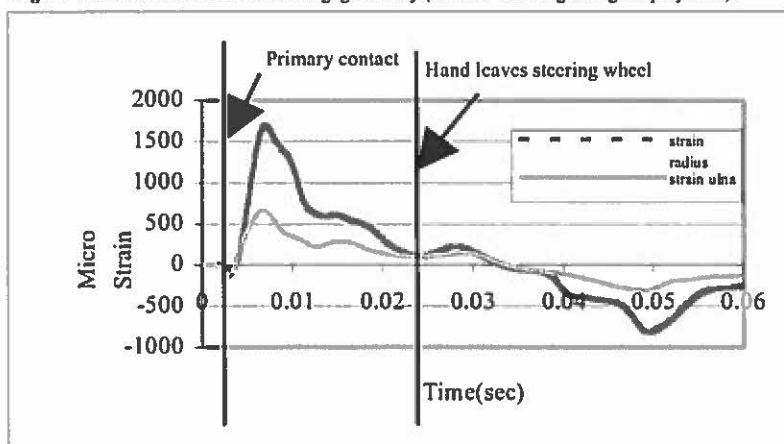


Figure 16: Crack detection gage history on cadaver 6L (Fracture case-Dual stage deployment).

primary contact occurred during 0-10 ms after which the hand released from the steering wheel at 12-18 ms and subsequently

contacted the body at 35-45 ms for the dummy and somewhat later for the cadaver. Conversely, all dual stage cadaver experiments experienced primary contact at 0-10 ms followed by a much later release of the hand at 35-40 ms.

The strain-time histories revealed positive axial radius and ulna surface strains, which correlated closely with the wrist acceleration-time history with a short (3 ms) time lag (Figure 15).

Analysis of the time history from one ulna crack detection affixed for a dual stage experiment showed a sharp response from the gage at approximately 30 ms (Figure 16). This specimen suffered an ulna fracture at the site of the crack detection gage and this time point correlates with the release of the hand from the steering wheel as well as the secondary peak resultant wrist acceleration (Figure 9B).

DISCUSSION

In the current study, we hypothesized that a deploying airbag can subject the forearm to varying degrees of primary contact injury risk based on forearm proximity and positioning and that this risk would be correlated with forearm kinematics. To address this hypothesis, we analyzed accident statistics to better understand the scope of the problem and later analyzed driver upper extremity positions in the field. This was followed by laboratory experiments using instrumented dummy and cadaver arms to test a variety of driver forearm positions.

Analysis of Accident Statistics: The NASS data indicates a relatively constant level of injury exposure. As the vehicle fleet is comprised of more airbag equipped vehicles and seat belts use becomes mandatory, common upper extremity injury modalities may change, while the overall injury risk may not. Additional analyses of European accident data by Richter, et al., (6) of non airbag equipped vehicles (pre 1995) show that that the hand, wrist, and forearm are equally likely to suffer fracture at an average ΔV of 19 mph (similar to the current study). Alternately, the 1995-99 NASS suggests that airbag deployments have created a bias toward forearm fracture.

Driver Upper Extremity positioning Study: Analysis of the forearm positions of 30 drivers from three discrete anthropometries revealed similarities in forearm-airbag positioning that were independent of subject size. For example, many subjects used a single, overhand grasp near the top or side of the wheel while several subjects from different anthropometries also used an underhand grasp. Overall analysis yielded five 'test' positions with close proximity and two 'control' (or assumed safe) positions. The current study identified overhand grasp positions consistent with previous experimental studies (14-17), which relied on biomechanical considerations to predict a worst case position for testing. An additional, unreported position in the literature was noted in the

current study in which an underhand grasp was used to facilitate a turn of the wheel.

Anthropomorphic dummy tests: The dummy tests revealed a wide variety of forearm kinematics based on arm positioning relative to the airbag. Grasping the neutral wheel with an overhand, bilateral grasp at the 9 and 3 o'clock positions may be the safest position based on forearm contact pressures, wrist accelerations and forces. All single overhand grasps, which placed the forearm over the airbag module, produced larger accelerations and contact pressures. The underhand grasp placing the forearm over the airbag with the wheel turned 90 degrees produced the greatest overall wrist loading, acceleration, velocity, and forearm contact pressures. As such, this position was selected for further study with cadaveric tissues to elucidate injury risks with this position. It is interesting to note that even though the dummy predicted greater load characteristics for this particular position, recent tests of isolated cadaveric forearms (18) indicate that the forearm fracture tolerance is 21% greater in bending when supinated (as tested cadaverically in the current study) versus the pronated position (as tested cadaverically in previous studies by (15-17)). This is due to the relative position of the radius and ulna leading to simultaneous loading (supinated and stronger) versus independent loading (pronated and weaker). This suggests that even though the dummy testing suggests elevated levels of loading, corresponding tests on cadavers might show an equal risk of fracture between over and underhand grasps even though the load levels are different. Currently, there is insufficient data from pair-matched vehicle environments to elucidate this question.

Peak accelerations in the current study occurred early in the event (~10 ms) and were generally 150-220 g for the non-control positions. These data are similar to Saul, et al., who report average resultant wrist accelerations of 303 g's (15) for a similarly instrumented dummy arm and an overhand grasp. These higher values as compared to the current study may be explained, in part, by different arm positions and the higher data filter used by Saul, et al., (CFC1000) versus the current study (CFC180). Our use of CFC180 was based on (16). While the instrumented arm used in the current study provided an efficient way to discriminate between different occupant forearm positions, future work may be needed to optimize the location and type of sensors to best correlate with developing injury indices.

Cadaver Tests: Two forearm fractures were produced with the underhand grasp and the dual stage air bag in 6 upper extremities harvested from different donors. A second set of tests using the contralateral arms from the fractured subjects yielded no injury with a single stage airbag deployment.

The resultant wrist acceleration plots exhibited a second peak, which correlated with the hand releasing from the steering wheel. This later time point correlated with an ulnar fracture and crack detection gage failure in one specimen, suggesting a different injury mechanism versus previous cadaver studies (15-17), which noted fracture earlier in the event. The peak accelerations were typically 400-500 g's, more than double those from the dummy testing for the same position and airbag deployment parameters. Interestingly, the peak acceleration magnitudes with the single stage air bag were greater than the pair-matched dual staged experiments (400 g's-dual stage vs. 600 g's-single stage). While this finding is somewhat paradoxical, it may reflect the more complex bag inflation event with the added resistance of the forearm versus normal inflation. Even though the acceleration peaks were different, the velocities from the dual stage were always greater than the single stage. In addition, plotting average acceleration and primary contact time data and fitting a curve through the data points revealed that the dual stage experiment fracture cases were in a region above the curve ('fracture region'), while the rest of the cases were below the curve ('non-fracture region') (Figure 14).

Differences between the cadaver and dummy are likely due to biofidelity issues as well as anthropometry differences between the cadavers and the 50th male dummy. The acceleration magnitudes from the current study are similar to the cadaver studies of Bass, et al., (530 g's) (16), but lower than that reported by Hardy, et al., (17) (700 g's). The similarities and differences between the current and past studies may be explained again by data filtering (Bass, et al., used CFC180 as in the current study while Hardy, et al., used CFC1000), variations in specimen anthropometry, tissue quality, and/or test boundary conditions (Bass, et al., and Hardy, et al., used both isolated upper extremities mounted to a fixture as well as intact cadavers). The wrist resultant velocities from the dual (3-5.5 m/s) and single stage (3-4 m/s) tests of the current study are significantly lower than the injury threshold velocity of 14 m/s reported by Hardy, et al. This may be attributed to the different filter classes employed on the original acceleration data, differences in forearm positioning (under- vs. over- hand) grasps, and the use of isolated-fixtured arms (16, 17) versus the inertial resistance of the body used in the current study. Additional variations in the mechanical response have been attributed to the quality of the bone of individual cadavers (17). While not assessed in the current study, such variations in bone quality might help explain the fracture frequencies noted in the dual stage testing. Regardless, however, the pair-matched experiments showed the effect of alterations in the manner in which the bag deployed as single stage deployments produced no fractures.

Future work is required to better understand common upper extremity positions in the field, which is a complex combination of stature, personal driving habits and probably a variety of other parameters. Perhaps drivers could be anonymously imaged while driving. Such data, analyzed in context with information derived from NASS, experimental investigations, advanced Finite Element models and on going clinical case studies, may help form the basis for injury prevention strategies.

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