INJURY CRITERIA FOR DYNAMIC HYPEREXTENSION OF THE FEMALE ELBOW JOINT

Stefan M. Duma*, Gail A. Hansen, Eric A. Kennedy, Joel D. Stitzel
Virginia Tech – Wake Forest, Center for Injury Biomechanics
Blacksburg, VA 24061

Frederick T. Brozoski
United States Army Aeromedical Research Laboratory
Fort Rucker, AL 36362

ABSTRACT

This paper describes an analysis to develop dynamic hyperextension injury criteria for the female elbow joint. Dynamic hyperextension tests were performed on 24 female cadaver elbow joints. The energy source was a drop tower utilizing a three-point bending configuration to apply elbow bending moments matching the previously conducted side airbag tests. Post-test necropsy showed that 16 of the 24 elbow joint tests resulted in injuries. Injury severity ranged from minor cartilage damage to more moderate joint dislocations and severe transverse fractures of the distal humerus. Peak elbow bending moments ranged from 42.4 Nm to 146.3 Nm. Peak bending moment proved to be a significant indicator of any elbow injury ($p = 0.02$) as well as elbow joint dislocation ($p = 0.01$). Logistic regression analyses were used to develop single and multiple variate injury risk functions. Using peak moment data for the entire test population, a 50% risk of obtaining any elbow injury was found at 56 Nm while a 50% risk of sustaining an elbow joint dislocation was found at 93 Nm for the female population. It is anticipated that this study will provide researchers with additional injury criteria for assessing upper extremity injury risk caused by both military and automotive side airbag deployments.

1. INTRODUCTION

While modern Army helicopters incorporate crashworthiness features such as energy-absorbing landing gear and seats, self-sealing fuel systems, and harness restraints, helicopter occupants continue to be at high risk of injury during survivable mishaps. A study performed by Shanahan (1989) demonstrated that approximately 80% of helicopter crash injuries are caused by impacts between the occupants and the aircraft structure. In particular, the severe and fatal injuries are predominately head injuries such as concussions and skull fractures that are attributed to head strikes with the interior structures. These injurious head strikes can occur even when the pilot is wearing the flight helmet and properly restrained with the five-point belt system that includes an inertia reel.

To reduce the incidence of severe injuries from helicopter crashes, the United States Army investigated incorporating frontal and side airbags as a supplemental restraint system in its helicopter fleet. Shanahan (1993) projected a 23% reduction of injuries and 50% reduction in fatalities from head injuries during survivable helicopter mishaps through the use of airbags. Based upon these studies, development of a Cockpit Airbag System (CABS) for retrofit into existing aircraft was begun in the mid-1990s. The US Army chose the UH-60A/L Black Hawk helicopter as the first aircraft for which a cockpit airbag system was designed. The helicopter crash event is complex and typically results from low altitude impact with trees, power lines, other aircraft, or gunfire. The resulting impact can include vertical, frontal and lateral acceleration components. Frontal airbags were installed to protect against frontal and vertical impacts. Side airbags were mounted outboard of each crewstation, affixed to a rigid side armor panel, providing occupant flail strike protection during lateral impacts with roll or yaw components.

Following preliminary tests with the CABS system, concerns arose over the risk of unnecessary deployments of the CABS and the subsequent threat of side airbag-induced upper extremity injury to occupants (McEntire, 2003). In particular, women have been considered the most vulnerable occupants to helicopter airbag loading due to their smaller stature, bone structure, and loss of bone mineral density, along with their increasing role in the military (Duma, 1999, 2003). Although upper limb injuries are not as life threatening as the potential head injuries, they may be critical if the airbags deploy inadvertently during flight. The CABS triggering system is based on processed accelerometer data measured from the aircraft frame. This system has the very difficult task of distinguishing between acceleration pulses from the helicopter's own large caliber guns, incoming gunfire, and ground crashes. Therefore, it is necessary to investigate the possibility of an inadvertent airbag deployment in flight that results in an upper extremity injury. If the injury is serious enough, such as a humerus fracture or elbow dislocation, the pilot may no longer be able to fly the aircraft, and an inadvertent deployment becomes a serious crash event.

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Previously, the interaction between a deploying side airbag and the upper extremity had shown by several studies to result in a range of upper extremity injuries. In tests with small female cadavers, Duma (1998) found chondral and osteochondral fractures in the elbow joint for seven out of the 12 cadaver tests that had been subjected to upper extremity loading from a deploying seat-mounted side airbag. A follow up study by Duma (2001) evaluated the same seat-mounted side airbag and the effect of a door mounted handgrip with six small female cadavers. The purpose of this study was to investigate injury resulting from moments to the elbow joint due to hyperextension under dynamic loading conditions similar to a cockpit side airbag deployment and to develop elbow injury criteria to assess upper extremity injury risk.

2. METHODOLOGY

A single dynamic hyperextension impact test was performed on 24 matched pair human cadaver upper extremities (12 cadavers). The energy source was a drop tower utilizing a three-point bending configuration to provide dynamic hyperextension of the elbow joint with bending moments matching the onset rate and momentum transfer of the previously conducted original CABS side airbag tests. All cadaver upper extremities were obtained from females 29 to 85 years old. Pre-test OsteoGrams were obtained for each upper extremity (Compumed, Inc., Los Angeles, CA). These OsteoGrams were used to examine the Bone Mineral Density (BMD) of the test subjects to identify if any specimen possessed a pre-existing osteoporotic condition. The OsteoGram data and test conditions for each subject are listed in Table 1.

The drop test configuration is depicted in Figure 1. To stabilize the upper extremity in the test configuration, the proximal two thirds of tissue was removed from the humerus and inserted into a rigid square aluminum potting cup with polymer filler (Bondo Corporation, Atlanta, GA). The head of the humerus was removed using a bone saw to ensure a proper fit into the potting cup. Each upper extremity was preconditioned manually by flexing and extending it 10 times prior to testing. To maintain bending in the sagittal plane, a semicircular roller support was attached to the wrist and the aluminum pot connected to the proximal humerus. The rollers at the ends of the specimen were then placed on greased horizontal reaction plates. The distance between the reaction plates was adjustable to accommodate the various lengths of the upper extremities used for the tests. The upper extremity was positioned on top of the reaction plates with the distal end to the right such that the impactor head would contact the humerus pot upon impact.

TABLE 1: Part II cadaver upper extremity data and test matrix.

Test ID	Subject Number	Aspect (Left/Right)	Age (years)	Mass (kg)	BMD Index	T-Score	Z-Score
2.01	1	Left	61	53.98	77.9	-3.0	-1.2
2.02	1	Right	61	53.98	77.9	-3.0	-1.2
2.03	2	Left	67	63.41	75.2	-3.3	-1.0
2.04	2	Right	67	63.41	75.2	-3.3	-1.0
2.05	3	Left	73	45.36	73.7	-3.4	-0.7
2.06	3	Right	73	45.36	73.7	-3.4	-0.7
2.07	4	Left	64	56.70	89.2	-2.0	0.0
2.08	4	Right	64	56.70	89.2	-2.0	0.0
2.09	9	Right	63	44.90	109.6	-0.1	1.6
2.10	8	Right	29	85.30	126.5	1.4	1.4
2.11	5	Right	59	79.40	124.4	1.3	2.3
2.12	6	Right	54	49.90	90.0	-1.9	-0.9
2.13	9	Left	63	44.90	109.6	-0.1	1.6
2.14	8	Left	29	85.30	126.5	1.4	1.4
2.15	5	Left	59	79.40	124.4	1.3	2.3
2.16	6	Left	54	49.90	90.0	-1.9	-0.9
2.17	7	Right	58	97.50	120.3	0.9	1.8
2.18	10	Right	65	60.30	88.9	-2.0	0.0
2.19	11	Right	85	52.20	74.3	-3.4	-0.4
2.20	12	Right	42	54.40	96.4	-1.3	-1.3
2.21	7	Left	58	97.50	120.3	0.9	1.8
2.22	10	Left	65	60.30	88.9	-2.0	0.0
2.23	11	Left	85	52.20	74.3	-3.4	-0.4
2.24	12	Left	42	54.40	96.4	-1.3	-1.3

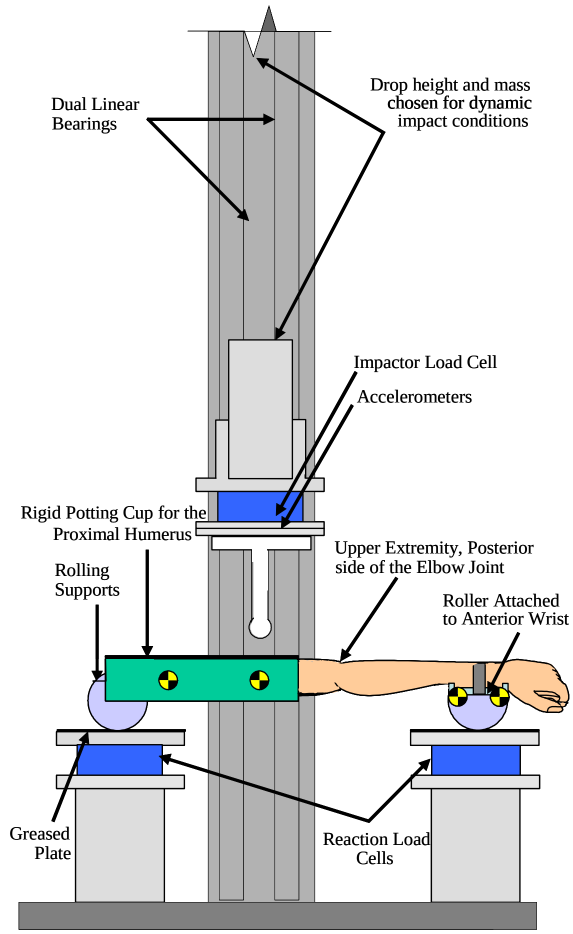

FIGURE 1: Drop test configuration for dynamic hyperextension of the cadaver elbow joint.

The upper extremities were randomly divided into two equal groups. Each group was subjected to one of the following impact scenarios: 9.75 kg impactor mass at a high-energy drop height of 0.910 m, or the same impactor mass at a low-energy drop height of 0.303 m. The impactor assembly traveled on four reciprocating roller bearings connected to two linear shafts to reduce lateral flexibility. Instrumentation included six-axis load cells placed on the impactor and two supports. The impactor load cell (Denton 1968, 22,240 N, Rochester Hills, MI) was used to measure forces exerted onto the specimen by the impactor. Each reaction plate was supported by a single reaction load cell (Denton 5768, 11,120 N, Rochester Hills, MI) that measured the forces exerted by each end of the upper extremity. An accelerometer (Endevco 7264B, 2000 G, San Juan Capistrano, CA) was attached to the impactor head to allow for inertial compensation of the mass between the upper extremity and active axis of the load cell. During the loading, the impactor head contacted a trigger strip positioned on top of the humerus pot to initiate the data acquisition for each test. Data from the load cells and accelerometers were recorded at a sampling frequency of 30,000 Hz with 16-bit Analog-to-Digital conversion resolution (Iotech WBK16, Cleveland, OH). Test kinematics were captured by high-speed video at 2,000 fps (Vision Research, Phantom IV, Wayne, NJ). All channels were filtered to CFC 600. In a study performed to recommend a filter class specification for the instrumented upper extremity, CFC 600 was recommended as the optimum filter class to use for upper extremity testing (Stitzel, 2002). For comparison to other tests, elbow moment onset rates were calculated for each test with respect to 25% and 75% of the signal range.

A statistical analysis was performed to characterize the forces that acted on the cadaver specimens and correlate them to the anatomic injury assessments of necropsy and ink staining. As a part of this analysis, a logistic regression analysis was performed to develop injury risk functions based upon experimental results. The binary subject variables were injury or no injury and specific injury outcome values, while the anthropometric and test data, such as mass and peak moment, were the independent test variables in this analysis. The specific input variables analyzed were age, specimen mass, BMD, pre-existing hyperextension, energy, and peak moment while the binary, injury output variables analyzed were injury, serious injury, fracture, dislocation/disruption, ligament damage, and cartilage damage.

3. RESULTS

Post-test necropsies showed that 16 of the 24 elbow joint tests resulted in injury. The engineering parameters and the types of injuries observed, either singularly or in combination are tabulated in Table 2. Injuries ranged in severity from minor cartilage lesions, ligament disruptions, and joint dislocations (AIS 1), to moderate anterior capsule tears, chondral fractures to the radial head and coronoid, (AIS 2), to the most serious transverse fractures of the distal humerus (Table 3). The various types of injuries consisted of fractures, joint dislocations, ligament damage, cartilage damage, or anterior capsule disruption. The types of chondral and osteochondral fractures that occurred were to the humerus, coronoid, radial head, trochlea, trochlear notch, and olecranon; examples are shown in Figures 2 and 3.

TABLE 2: Elbow moments and injuries from cadaver elbow joint drop tests.

Test ID	Subject Number	Aspect (Left/Right)	Drop Height (m)	Peak Elbow Moment (Nm)	Elbow Moment Onset Rate (Nm/ms)	Summary of Injury Outputs		
						Any Injury (Y/N)	Any Serious Injury (Y/N)	Fracture (Y/N)
2.01	1	Left	0.910	86.1	46	Yes	Yes	Yes
2.02	1	Right	0.303	58.3	14	No	No	No
2.03	2	Left	0.303	42.4	10	Yes	Yes	Yes
2.04	2	Right	0.910	68.9	13	Yes	Yes	Yes
2.05	3	Left	0.910	77.8	39	Yes	Yes	Yes
2.06	3	Right	0.303	45.3	113	No	No	No
2.07	4	Left	0.303	49.6	40	Yes	No	No
2.08	4	Right	0.910	92.7	98	Yes	Yes	Yes
2.09	9	Right	0.303	60.9	64	No	No	No
2.10	8	Right	0.910	141.7	72	Yes	No	No
2.11	5	Right	0.303	55.0	20	Yes	Yes	Yes
2.12	6	Right	0.910	52.6	50	Yes	Yes	Yes
2.13	9	Left	0.910	146.3	43	Yes	Yes	Yes
2.14	8	Left	0.303	83.0	22	No	No	No
2.15	5	Left	0.910	90.1	76	Yes	Yes	Yes
2.16	6	Left	0.303	55.9	31	No	No	No
2.17	7	Right	0.303	71.6	10	No	No	No
2.18	10	Right	0.910	89.1	36	Yes	Yes	Yes
2.19	11	Right	0.303	49.8	23	No	No	No
2.20	12	Right	0.910	102.1	16	Yes	Yes	No
2.21	7	Left	0.910	113.0	14	Yes	Yes	No
2.22	10	Left	0.303	60.2	15	Yes	Yes	Yes
2.23	11	Left	0.910	75.8	24	Yes	Yes	Yes
2.24	12	Left	0.303	47.9	9	No	No	No

TABLE 3: Elbow injuries of each cadaver specimen during the Part II dynamic loading tests.

Test ID	Test Energy	Injuries Observed	AIS Value
2.01	High	• Comminuted transverse fracture of distal humerus at elbow • Chondral fracture of the coronoid	3 2
2.02	Low	No injury	0
2.03	Low	• Avulsion/Osteochondral fracture of the coronoid	2
2.04	High	• Osteochondral fracture of olecranon • Anterior elbow ligament disruption	2 1
2.05	High	• Extra-articular fracture of distal humerus	3
2.06	Low	No injury	0
2.07	Low	• Disruption of the anterior capsule, anterior laterally on radial side of joint	2
2.08	High	• Condylar fracture to the trochlea • Dislocation of elbow joint	2 1
2.09	Low	No injury	0
2.10	High	• Disruption of the anterior capsule	2
2.11	Low	• Fracture/fragment of coronoid process • Fracture/fragment of distal trochlear notch • Partial tear to radial head ligamentus	3 3 1
2.12	High	• Extra-articular, supracondylar fracture of distal humerus	3
2.13	High	• Fracture/fragment of edge of coronoid process • Fracture medial of coronoid process • Anterior dislocation of elbow joint	3 3 1
2.14	Low	No injury	0
2.15	High	• Comminuted fracture of distal humerus	3
2.16	Low	No injury	0
2.17	Low	No injury	0
2.18	High	• Supracondylar fracture of distal humerus at the trochlea • Chondral lesion to radial head • Chondral fracture of radial head	3 1 2
2.19	Low	No injury	0
2.20	High	• Dislocation of elbow joint	1
2.21	High	• Medial/lateral ligaments nearly completely torn • Dislocation of elbow joint	1 1
2.22	Low	• Extra-articular, supracondylar fracture of distal humerus	3
2.23	High	• Fracture/fragment of coronoid process • Ligaments completely torn apart functionally • Anterior dislocation of elbow joint	3 1 1
2.24	Low	No injury	0

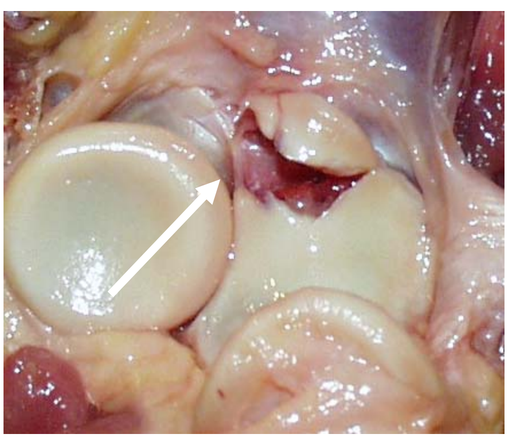

FIGURE 2: Test 2.03 - Avulsion, osteochondral fracture of the coronoid.

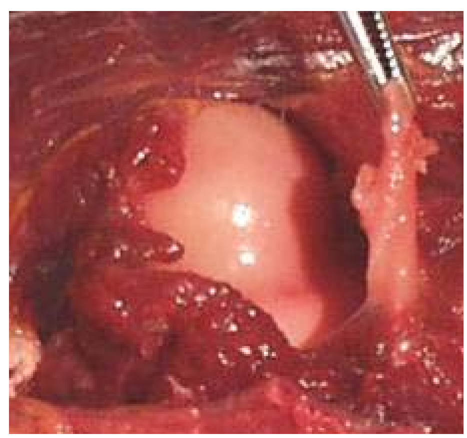

FIGURE 3: Test 2.10 - Disruption of the anterior capsule.

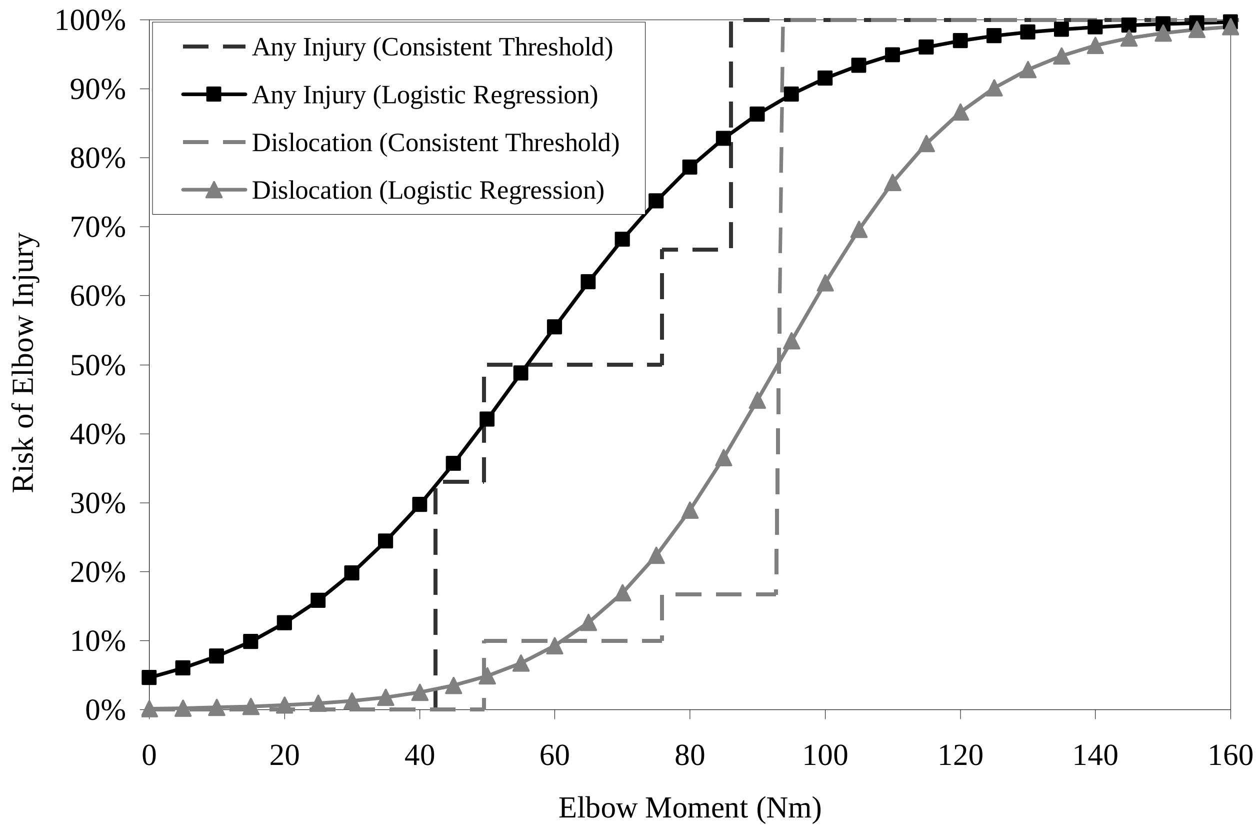

FIGURE 4: Risk of any elbow injury (p = 0.02) or elbow joint dislocation (p = 0.01) based upon peak elbow bending moment.

Peak elbow bending moment proved to be a significant indicator of the predicted risk of any elbow injury and the predicted risk of elbow joint dislocation (p = 0.019, p = 0.009). Again, all relationships between energy and the output variables, minus ligament and cartilage damage, were found to be significant as could be expected. Also, a significant relationship was found between age and ligament damage as well as specimen mass and ligament damage (p = 0.026, p = 0.030). All 24 dynamic hyperextension impact tests were included in the analysis that produced single variate risk functions for any elbow injury or joint dislocation with respect to the peak elbow bending moment applied during the test. (Figure 4).

4. DISCUSSION

The newly developed elbow injury risk functions predict a 50% risk of any elbow injury at 56 Nm with a 100% probability of any elbow injury at 186 Nm. Also, at 93 Nm and 194 Nm, this risk function calculates a 50% and 100% risk of elbow joint dislocation, respectively. In other words, for a given percent risk of injury, it is observed that the moment required to cause dislocation of the elbow joint is higher than the moment required to offer the same risk of a non-specific injury. This could be caused by the fact that a brittle bone fracture may require less force than the dislocation of a strong elbow joint. Taking into account the broad range of human specimen age and BMD data presented in this current study further strengthens this argument. Therefore, if a bone fracture does not initially occur, the force is able to continue to increase to a point at which it is able to dislocate the joint. Also, less force is required to incur minor injuries, such as minor cartilage lesions and ligament disruptions, which are included in the risk for any injury. Furthermore, it is noted that all joint dislocations (AIS 1) occurred during only high-energy tests while more serious injuries such as fractures (AIS 3) occurred in both energy levels. Although extra-articular fractures may be considered serious on a threat to life scale, they are medically simpler to repair with less long term pain. In contrast, elbow joint dislocation can lead to long term pain and even loss of functionality if the condition becomes arthritic.

The mechanism for injury about the elbow joint was assumed a priori to be pure moment due to dynamic hyperextension. As such, no other input parameters were examined in the statistical analysis. It is possible that some other physical variable would show better correlation with injury. At the tissue level, there are multiple injury mechanisms to consider such as tensile stresses to the ligaments and compressive stresses to the cartilage. These local injury mechanisms are too complex to analyze for the current study, which was only focused on the effects of global hyperextension to the elbow joint.

It is important to consider that the average age of the specimens tested in this study was 60 ± 14 years. It is understood that most specimens used in this study were older than the female aviators this study was intended to protect. This is not uncommon for biomechanics testing where the age range of test subjects is typically oversampled from the elderly population. Application of injury criteria developed from these test subjects therefore is usually conservative and actually serves to overestimate injury risk for younger population subsets.

It is important to note that the principal function of the Black Hawk side airbag system is to minimize the risk of serious to fatal injuries. In lateral dynamic impacts both the original and redesigned side airbag offer substantial occupant protection relative to serious head injuries. Optimizing the side airbag in order to keep its serious injury mitigating properties while minimizing the risk of less severe upper extremity injuries is a very complex issue. One critical factor to consider for the Black Hawk helicopter environment is the risk of inadvertent airbag deployment from incoming small or large arms fire. While a dislocated elbow is not life threatening, if it occurs as a result of an inadvertent deployment while at altitude, the pilot may not be able to continue flying and subsequently crash the aircraft. Then the minor elbow injury can become equivalent in some aspects to the more severe injuries. Considerable effort was put into the airbag trigger circuit to prevent inadvertent deployment, but this is a good example of just one of the complex issues to consider when optimizing the side airbag.

5. CONCLUSION

Peak bending moment proved to be a significant indicator of any elbow injury ($p = 0.02$) as well as elbow joint dislocation ($p = 0.01$). Using peak elbow bending moment data for the entire test population, a 50% risk of obtaining any elbow injury was found at 56 Nm while a 50% risk of sustaining an elbow joint dislocation was found at 93 Nm for the female specimen. These results indicate that the peak elbow bending moments achieved in Part I are associated with a greater than 90% risk for elbow injury. This risk assessment revealed a high risk of injury to the upper extremities in the event of an inadvertent deployment of the original helicopter side airbag system. Subsequently, the airbag was re-designed in an effort to mitigate upper extremity injury risks. This study provides researchers with a comprehensive set of injury criteria for assessing upper extremity injury risk caused by side airbag deployments. This research can also be applied to the design improvement of other helicopter side airbag systems to prevent and reduce injuries to the occupants.

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