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Risk Functions for Human and Porcine Eye Rupture Based on Projectile Characteristics of Blunt Objects

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ABSTRACT – Eye ruptures are among the most devastating eye injuries and can occur in automobile crashes, sporting impacts, and military events, where blunt projectile impacts to the eye can be encountered. The purpose of this study was to develop injury risk functions for globe rupture of both human and porcine eyes from blunt projectile impacts. This study was completed in two parts by combining published eye experiments with new test data. In the first part, data from 57 eye impact tests that were reported in the literature were analyzed. Projectile characteristics such as mass, cross-sectional area, and velocity, as well as injury outcome were noted for all tests. Data were sorted by species type and areas were identified where a paucity of data existed, based on the kinetic and normalized energy of assaulting objects. For the second part, a total of 126 projectile tests were performed on human and porcine eyes. Projectiles used for these tests included blunt aluminum projectiles, BBs, foam pellets, Airsoft pellets, and paintballs. Data for each projectile were recorded prior to testing and high-speed video was used to determine projectile velocity prior to striking the eye. In part three the data were pooled for a total of 183 eye impact tests, 83 human and 100 porcine, and were analyzed to develop the injury risk criteria. Binary logistic regression was used to develop injury risk functions based on kinetic and normalized energy. Probit analysis was used to estimate confidence intervals for the injury risk functions. Porcine eyes were found to be significantly stronger than human eyes in resisting globe rupture ($p=0.01$). For porcine eyes a 50% risk of globe rupture was found to be 71,145 J/m^2, with a confidence interval of 63,245 J/m^2 to 80,390 J/m^2. Human eyes were found to have a 50% risk of globe rupture at a lower, 35,519 J/m^2, with confidence intervals of 32,018 J/m^2 to 40,641 J/m^2. The results presented in this paper are useful in estimating the risk of globe rupture when projectile parameters are known, or can be used to validate computational eye models.

KEYWORDS – Eye, Globe, Rupture, Human, Porcine, Risk Function, Projectile, Injury

INTRODUCTION

Injury Background

There are over 1.9 million eye injuries per year in the United States (McGwin 2005). The incidence of severe eye injuries is on the same order of magnitude of the number of passengers killed in vehicle crashes every year, with approximately 30,000 Americans left blind in one eye as a result of trauma (Parver 1986). Some of the most severe eye injuries can occur in automobile accidents, from sports related impacts, and from military accidents and causalities (Chisholm 1969, Berger 1978, Mader 1993, Duma 1996, Vinger 1997, Kuhn 2000, Duma 2002, Rodriguez 2003).

Blunt impact of the eye with an airbag or other objects can result in severe eye injury such as hyphema (bleeding in the anterior chamber of the eye), lens dislocation, or globe rupture (Chisholm 1969, Vichnin 1995, Duma 1996, Ghafouri 1997, Stein 1999, Lueder 2000, Power 2002, Hansen 2003, Stitzel 2005). Although not statistically significant ($p=0.15$), eye injuries sustained during automobile crashes occur at a higher rate (3.1%) when the occupant is exposed to a deploying airbag than when the occupant is not (2.0%) (Duma 2002). The airbag has been shown to be both directly responsible for eye injuries from blunt impact with the eye and indirectly responsible for eye injuries by propelling objects into the eye during the airbag deployment (Kuhn 1995, Duma 2002). Though no experimental studies have been reported that have specifically shown airbags to cause globe rupture, computational simulations have shown airbag interaction with the eye to lead to high corneo-scleral stress (Stitzel 2005). Additionally, several case studies in the literature specifically cite airbags as the primary cause of globe rupture, although this injury mechanism appears to be very rare (Kuhn 1994, Duma 1996, Pearlman 2001).

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Eye injuries in sporting activities are also common, due to the close proximity of players and high energies involved. Globe rupture can occur from blunt trauma from many sports objects such as baseballs, golf balls, hockey sticks, squash balls and other objects (Chisholm 1969, Vinger 1996, Vinger 1999, Rodriguez 2003). Paintballs have also proven to have a devastating effect on the unprotected eye, often resulting in complete rupture of the globe and loss of intraocular contents, hyphema, retinal tearing, and traumatic cataracts are also very prevalent (Vinger 1997, Thach 1999, Fineman 2000, Listman 2004).

Eye injuries in the military environment are even more prevalent and are generally more severe than eye injuries to civilians. The rate of eye injuries has dramatically increased in warfare since the American Civil War (Figure 1) (Heier 1993). Eye injuries in World War I and World War II accounted for approximately 2.0% to 2.5% of all injuries, during the U.S. involvement in Vietnam, this percentage increased to 5% to 9%; in recent conflicts, such as Operation Desert Storm, the percentage of eye injuries has dramatically increased to over 13% of all combat injuries (Stone 1950, Heier 1993, Wong 2000). While many of the conflict-related eye injuries are caused by shrapnel and other debris, nearly 25% of the injuries are also caused by blunt trauma from motor-vehicle and helicopter crashes, falling, and direct hits from blunt objects (Mader 1993, Biehl 1999).

Previous Research

Previous researchers have performed eye impact tests to determine the injury tolerance of eyes to a variety of blunt objects (Weidenthal 1964, Weidenthal 1966, Delori 1969, McKnight 1988, Green 1990, Duma 2000, Scott 2000, Stitzel 2002).

A study performed by Weidenthal and Schepens (1966) conducted BB impact experiments on over 235 porcine eyes. Similarly, over 75 BB impacts with porcine eyes and one set of human eyes were conducted by Delori et al. (1969). Unfortunately, insufficient data is presented to account for the specific injury pathologies and the frequency at which these injuries occurred.

Two experimental studies were performed to examine less severe eye injuries. Duma et al. (2000) performed a series of foam particle tests on 21 porcine eyes and developed an injury risk function based on kinetic energy to predict the risk of corneal abrasion. Globe rupture was not observed in any tests. Scott et al. (2000) used 21 enucleated porcine eyes for eye impact tests using three different blunt metal rods. An injury risk function was developed to

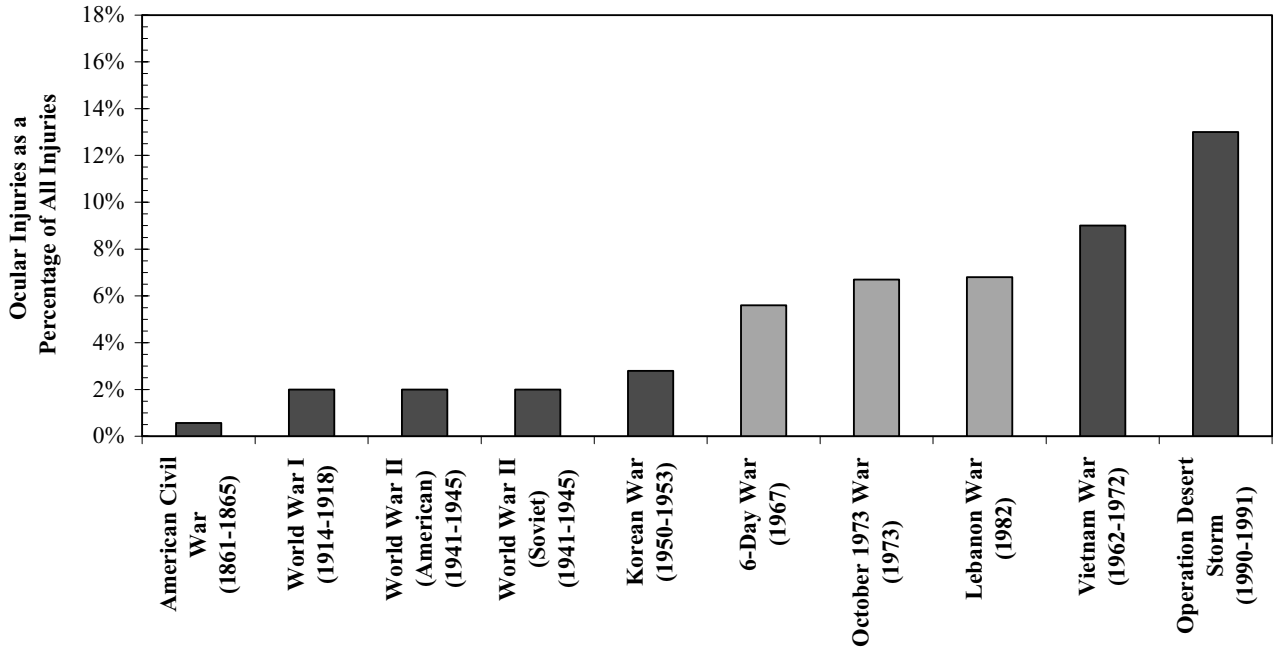


Figure 1: Ocular injuries shown as a percentage of total war injuries from 1861 to present.

predict the likelihood of various severity injuries, such as lens damage, lens dislocation, and retinal damage. It was observed that lens dislocations occurred at a kinetic energy of approximately 0.75 J and retinal damage at approximately 1.20 J. Globe rupture was not observed in any of the tests.

Stitzel et al. (2002) performed a series of 22 eye impact tests on enucleated human eyes using foam projectiles, BBs, and baseballs. The results of these tests were used to validate a failure stress level for a computational eye model. In the experimental tests, globe rupture was observed to occur from both BB impacts and baseball impacts. Globe rupture from BBs was observed at a kinetic energy level of 1.36 J and greater, while impacts at 0.67 J or less resulted in no injury. A baseball impact of 66 J resulted in no injury; however, other baseball impacts from 87 J and greater all resulted in globe rupture. Baseball tests resulted in interaction of the baseball to the edge of the simulated orbits used for testing; therefore, it is impossible to estimate the amount of energy that was directly transferred to the eye.

Others have performed impact experiments on various species of animals for the purposes of determining injury mechanisms for eye injuries, as well as the effect of corrective surgery in reducing the strength of the eye. These surrogate animals are used for testing because they are more readily available than post-mortem human eyes, and in the case of some researchers, in vivo tests were performed on anesthetized animals.

Weidenthal (1964) conducted blunt trauma impact experiments using live rhesus monkeys to determine the force required to separate the ciliary body from the sclera and to cause globe rupture. McKnight et al. (1988) used cat eyes to investigate the effects of radial keratotomy (RK) in reducing the corneal strength of the eye. Green et al. (1990) conducted projectile tests on anesthetized monkeys to determine the fracture tolerance of the orbital floor, while also noting eye injury pathology. Galler et al. (1995) also used porcine eyes to evaluate the effects of photorefractive keratectomy (PRK) and automated lamellar keratectomy (ALK) surgery in reducing corneo-scleral integrity. Peacock et al. (1997) impacted surgically altered human eyes from ALK, RK, PRK, and Laser-assisted in situ Keratomileusis (LASIK) to observe differences in the injury tolerance resulting from these surgical techniques.

Each of the previously reported studies are limited by one or more of the following factors: the number of tests performed, the range of projectile size, mass, or impact velocities used, and the detail in which resulting injury pathologies are reported. As such, due to the limitations of the available dataset no previous studies have been able to develop comprehensive injury criteria for human or porcine eyes for globe rupture. Therefore, the purpose of the current study is to pool the available data on globe rupture, increase the amount of available data through additional experimental tests, and develop injury risk functions for globe rupture from blunt projectile impacts. These risk functions can then be used for evaluation of current products and objects where it is desired to determine eye injury potential; also, these can be used in the design of new products so that their injury potential can be quantified prior even to fabrication. Given that porcine eyes are frequently used as surrogates for human eyes in impact studies, an additional goal of this study is to compare the relative strength of human eyes and porcine eyes to globe rupture.

METHODS

The current study is comprised of three parts. In Part 1, existing data from blunt ocular impact studies were collected from the literature. The existing data were pooled and evaluated to determine areas where a paucity of data existed. Next, regions were identified where additional data were necessary. For Part 2, experimental impact tests were performed using a variety of objects to develop a complete database for globe rupture using both human and porcine eyes. In Part 3, the data from both parts were combined and then the total database was analyzed to develop injury risk functions for both human and porcine eyes from blunt projectile impact.

Part 1: Published Experiments

An analysis of previous experiments was conducted in which data were sorted according to projectile characteristics such as type, mass, diameter, and velocities, as well as injury outcome. Since the purpose of this study was to elucidate any differences between human and porcine eyes, specimens were limited to only human or porcine eyes. Parameters such as velocity, kinetic energy, and normalized energy were calculated for each test and used to determine where additional experimental test data were necessary. The normalized energy is defined as the energy per projected area of the projectile (Equation 1). The projected area is the contact surface area for a flat impacting object or the cross-sectional area of a sphere.

$$Normalized\ Energy\ \left(\frac{kg}{s^2}\right) = \frac{Kinetic\ Energy}{Projected\ Area} = \frac{\frac{1}{2}mv^2}{\pi r^2}\ (for\ a\ sphere) \quad \text{Eq.(1)}$$

Only unoperated eyes were included in this study because eyes that have undergone radial keratotomy (RK) are known to sustain open globe injury at lower energy levels than eyes without RK (McKnight 1988, Galler 1995, Peacock 1997, Vinger 2005). For each test, the occurrence or lack of occurrence of globe rupture was noted.

Part 2: Experimental Test Methods

A total of 126 additional impact tests were conducted in order to supplement the amount of available data for both human and porcine globe rupture. All tests were conducted by striking the cornea directly with objects of varying size and velocity. Each combination of object size, mass and velocity was carefully selected to add experimental data where a paucity of data previously existed.

Prior to testing, human and porcine eyes were harvested within 24 hours of death. Hydration of the eyes was maintained by storage in a saline-filled specimen jar and refrigerated fresh prior to testing. For testing, the eyes were removed from refrigeration and kept hydrated as they returned to room temperature just prior to the actual testing. All test procedures were reviewed and approved by the Virginia Tech Institutional Review Board.

For each test, the human or porcine eye was mounted in a simulated polycarbonate orbit (Figure 2). The eye was encapsulated in the orbit by a 10% gelatin solution which has been used previously to represent the extraocular tissue surrounding the eye in the orbit (Vinger 1999, Stitzel 2002). The gelatin was filled inside the simulated orbit to the posterior limbus. The dimensions of the orbit of 53 mm in the anterior-posterior direction, 41 mm in the superior-inferior direction, and 48 mm in the medial-lateral direction, and were selected to represent the approximate size of a human orbit (Stitzel 2002). The porcine eyes were potted in the same simulated orbits as the human eyes. The simulated orbit was mounted inside an enclosed plexiglass gallery where projectile testing could be safely conducted.

Four mechanisms were used to propel the projectiles used in this testing. Projectiles included Airsoft pellets fired from Airsoft pellet guns (Cybergun S.A., Beretta Softair - Beretta 92FS Spring, France and HFC, M80.45 Series Model "Combat Commander" Gas Gun, Taiwan), paintballs fired from a paintball gun (Kingman, Spyder TL-X, Baldwin Park, CA), foam projectiles and BBs from a BB rifle (Daisy Outdoor Products, Model 880, Rogers, AR), and aluminum and plastic projectiles from a custom

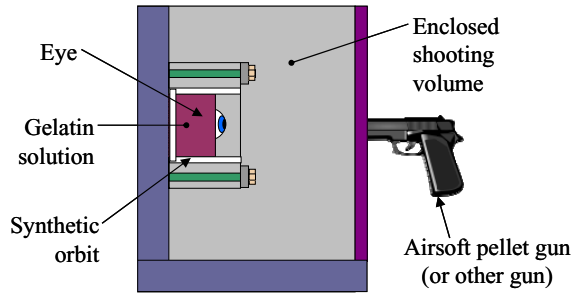


Figure 2: Experimental testing was performed in an enclosed shooting gallery from a distance of 175mm, and the eyes were contained in a synthetic orbit by a 10% gelatin solution.

designed pneumatic cannon. All eyes were struck directly at the center of the cornea.

High-speed video (Phantom 4, Vision Research, Inc., Wayne, NJ) at 7400 frames/second was used to visualize the response of the eye as it was impacted by oncoming projectiles, as well as to calculate the velocity of the projectile when it was approximately 10 mm to 30 mm from striking the eye. Binary injury response data were collected for each test specimen based on visual and photographic documentation of globe rupture or corneal-scleral laceration (or no injury) for each test scenario. Kinetic energy (J) and normalized energy (J/m^2) were then calculated to elucidate the relationship of these quantities to injury response.

Part 3: Data Analysis Methods

Results from Part I and Part II were combined into a database which was then used for all subsequent data analysis. Predictors used in the statistical analysis include the projectile diameter, projectile mass, projectile velocity, the kinetic energy of the projectile, and the normalized energy of the projectile. For each individual test, kinetic energy was calculated based on reported projectile mass and velocity. The normalized energy was analyzed as it has previously been shown to be a more significant injury predictor than kinetic energy alone (Duma 2005).

Logistic regression analyses were performed on the experimental data to determine significant predictors for eye injury based on p-values and Goodman-Kruskal Gamma values. P-values of 0.05 or less were interpreted to be statistically significant. For Goodman-Kruskal Gamma values, a correlation coefficient with values near 0.0 indicates no association between two subjects and a value of 1.0 represents a high association between predictor and injury (Collett 1991, Allison 1999).

A general form of the logistic regression injury risk function (Equation 2) can be used with specific injury parameters to predict the probability of globe rupture given a projectile's normalized energy or kinetic energy. The variable "x" refers to the level of input (such as kinetic energy or normalized energy) of the projectile onto the eye. The variables "a" and "b" are constants determined from the logistic regression and are unique to the specific predictor used (kinetic energy or normalized energy).

$$\text{Probability of Injury (\%)} = \frac{1}{1+e^{a-bx}} \qquad \text{Eq.(2)}$$

Additionally, a probit analysis was used in conjunction with the logistic regression analysis in order to estimate confidence intervals for the injury risk model (Collett 1991, Allison 1999). Confidence intervals from 5% to 95% were calculated assuming a logistic distribution.

In order to confirm the applicability of logistic regression analysis for the development of parametric injury risk functions, risk functions were also developed using the Consistent-Threshold (CT) technique, the modified median rank method, and the certainty method. These techniques have been previously suggested for analysis of biological data, in particular for doubly censored data (Mertz 1996, Eppinger 1999, DiDomenico 2003, Kent 2004). Results of the comparisons between the various risk functions are presented in the discussion section.

RESULTS

Part 1: Results from Published Experiments

A total of 57 impact tests were collected and analyzed from published studies. Of these, 35 tests were conducted on porcine eyes (Table 1) (Duma 2000, Scott 2000). Objects used for the eye impact tests were foam particles and a steel rod.

Another 22 tests were analyzed that utilized human eyes (Table 2) (Delori 1969, Stitzel 2002). These tests utilized objects such as foam, a baseball, and BBs. In these tests, there were approximately 17 non-injury tests and 5 injury tests.

Table 1: Test results reported in the literature from previous eye impact tests on porcine eyes.

Test	Author (Year)	Object	Projectile Diameter (mm)	Projectile Mass (g)	Projectile Velocity (m/s)	Kinetic Energy (J)	Normalized Energy (J/m^2)	Globe Rupture (Yes / No)
PL-1	Duma (2000)	Foam	12.50	0.30	4.80	0.00	28	No
PL-2	Duma (2000)	Foam	12.50	0.30	5.60	0.00	38	No
PL-3	Duma (2000)	Foam	12.50	0.30	7.00	0.01	59	No
PL-4	Duma (2000)	Foam	12.50	0.21	18.30	0.03	280	No
PL-5	Duma (2000)	Foam	12.50	0.16	25.50	0.05	411	No
PL-6	Duma (2000)	Foam	12.50	0.16	39.30	0.12	975	No
PL-7	Duma (2000)	Foam	12.50	0.16	41.60	0.13	1093	No
PL-8	Duma (2000)	Foam	12.50	0.16	46.00	0.16	1336	No
PL-9	Duma (2000)	Foam	12.50	0.57	26.80	0.21	1671	No
PL-10	Duma (2000)	Foam	12.50	0.55	29.90	0.25	2007	No
PL-11	Duma (2000)	Foam	12.50	0.58	29.90	0.26	2124	No
PL-12	Duma (2000)	Foam	12.50	0.16	57.70	0.27	2225	No
PL-13	Duma (2000)	Foam	12.50	0.55	31.70	0.28	2244	No
PL-14	Duma (2000)	Foam	12.50	0.21	57.70	0.35	2876	No
PL-15	Duma (2000)	Foam	12.50	0.17	87.60	0.63	5159	No
PL-16	Duma (2000)	Foam	12.50	0.55	72.40	1.44	11768	No
PL-17	Scott (2000)	Steel Rod	9.53	45.50	4.00	0.36	5103	No
PL-18	Scott (2000)	Steel Rod	9.53	45.50	4.30	0.42	5897	No
PL-19	Scott (2000)	Steel Rod	9.53	45.50	5.20	0.62	8624	No
PL-20	Scott (2000)	Steel Rod	6.35	3.50	18.90	0.63	19739	No
PL-21	Scott (2000)	Steel Rod	6.35	3.50	19.20	0.65	20371	No
PL-22	Scott (2000)	Steel Rod	6.35	2.60	23.80	0.74	23252	No

Table 1 (cont.): Test results reported in the literature from previous eye impact tests on porcine eyes.

Test	Author (Year)	Object	Projectile Diameter (mm)	Projectile Mass (g)	Projectile Velocity (m/s)	Kinetic Energy (J)	Normalized Energy (J/m^2)	Globe Rupture (Yes / No)
PL-23	Scott (2000)	Steel Rod	6.35	2.60	23.80	0.74	23252	No
PL-24	Scott (2000)	Steel Rod	6.35	3.50	20.70	0.75	23678	No
PL-25	Scott (2000)	Steel Rod	6.35	2.60	27.10	0.95	30147	No
PL-26	Scott (2000)	Steel Rod	6.35	3.50	26.20	1.20	37932	No
PL-27	Scott (2000)	Steel Rod	6.35	2.60	30.50	1.21	38186	No
PL-28	Scott (2000)	Steel Rod	6.35	2.60	32.30	1.36	42826	No
PL-29	Scott (2000)	Steel Rod	6.35	2.60	33.20	1.43	45246	No
PL-30	Scott (2000)	Steel Rod	6.35	2.60	36.00	1.68	53200	No
PL-31	Scott (2000)	Steel Rod	6.35	2.60	38.10	1.89	59588	No
PL-32	Scott (2000)	Steel Rod	6.35	3.50	33.00	1.91	60177	No
PL-33	Scott (2000)	Steel Rod	6.35	3.50	18.60	0.61	19117	No
PL-34	Scott (2000)	Steel Rod	6.35	45.50	5.20	0.62	19425	No
PL-35	Scott (2000)	Steel Rod	6.35	3.50	20.70	0.75	23678	No

Table 2: Test results reported in the literature from previous eye impact tests on human eyes.

Test	Author (Year)	Object	Projectile Diameter (mm)	Projectile Mass (g)	Projectile Velocity (m/s)	Kinetic Energy (J)	Normalized Energy (J/m^2)	Globe Rupture (Yes / No)
HL-1	Delori (1969)	BB	4.50	0.35	71.93	0.91	56930	Yes
HL-2	Stitzel (2002)	Foam	6.35	0.08	4.30	0.00	22	No
HL-3	Stitzel (2002)	Foam	6.35	0.08	5.40	0.00	35	No
HL-4	Stitzel (2002)	Foam	6.35	0.08	6.00	0.00	44	No
HL-5	Stitzel (2002)	Foam	6.35	0.08	10.60	0.00	137	No
HL-6	Stitzel (2002)	Foam	6.35	0.08	14.20	0.01	245	No
HL-7	Stitzel (2002)	Foam	6.35	0.08	14.30	0.01	249	No
HL-8	Stitzel (2002)	Foam	6.35	0.08	18.90	0.01	434	No
HL-9	Stitzel (2002)	Foam	6.35	0.08	23.00	0.02	643	No
HL-10	Stitzel (2002)	Foam	6.35	0.08	26.70	0.03	867	No
HL-11	Stitzel (2002)	Foam	6.35	0.08	26.80	0.03	873	No
HL-12	Stitzel (2002)	Foam	6.35	0.08	28.60	0.03	994	No
HL-13	Stitzel (2002)	Foam	6.35	0.08	31.00	0.04	1168	No
HL-14	Stitzel (2002)	Baseball	76.10	146.50	30.10	66.37	14591	No
HL-15	Stitzel (2002)	BB	4.50	0.38	53.00	0.53	33116	No
HL-16	Stitzel (2002)	BB	4.50	0.38	53.80	0.54	34123	No
HL-17	Stitzel (2002)	BB	4.50	0.38	55.80	0.58	36707	No
HL-18	Stitzel (2002)	BB	4.50	0.38	59.70	0.67	42018	No
HL-19	Stitzel (2002)	BB	4.50	0.38	85.20	1.36	85579	Yes
HL-20	Stitzel (2002)	BB	4.50	0.38	90.40	1.53	96344	Yes
HL-21	Stitzel (2002)	BB	4.50	0.38	91.70	1.58	99135	Yes
HL-22	Stitzel (2002)	BB	4.50	0.38	122.40	2.81	176624	Yes

Part 2: Experimental Results

A total of 126 experimental eye impact tests were performed. Of these, 65 tests were conducted on porcine eyes (Table 3). Objects used for the eye impact tests were Airsoft pellets, BBs, paintballs, foam particles, plastic rods, and aluminum rods. A total of 42 non-injury tests were conducted, along with 23 tests that resulted in globe rupture.

In addition, 61 tests were performed with human eyes (Table 4). These tests utilized objects such as Airsoft pellets, BBs, paintballs, foam particles, plastic rods, and aluminum rods. A total of 39 non-injury tests were performed, and globe rupture was noted for 22 tests.

A comparison of high-speed video of two separate impact tests is shown (Figure 3). Both tests were conducted with an 11 mm aluminum rod traveling at approximately 40 m/s ± 3 m/s. The test on the left was a porcine eye which did not rupture, compared to the human eye on the right, which experienced globe rupture.

Table 3: Test results from experimental eye impact tests on porcine eyes.

Test	Author (Year)	Object	Projectile Diameter (mm)	Projectile Mass (g)	Projectile Velocity (m/s)	Kinetic Energy (J)	Normalized Energy (J/m^2)	Globe Rupture (Yes / No)
PE-1	Present Study	Airsoft Pellet	6.00	0.12	97.78	0.56	19746	No
PE-2	Present Study	Airsoft Pellet	6.00	0.12	101.75	0.60	21384	No
PE-3	Present Study	Airsoft Pellet	6.00	0.11	94.65	0.51	18110	No
PE-4	Present Study	Airsoft Pellet	6.00	0.12	115.63	0.77	27330	No
PE-5	Present Study	Paintball	17.30	3.21	71.69	8.24	35061	No
PE-6	Present Study	Paintball	17.30	3.17	99.03	15.53	66070	No
PE-7	Present Study	Paintball	17.30	3.21	106.10	18.06	76837	Yes
PE-8	Present Study	Paintball	17.30	3.17	108.94	18.81	80003	Yes
PE-9	Present Study	Airsoft Pellet	6.00	0.20	74.65	0.57	20125	No
PE-10	Present Study	Airsoft Pellet	6.00	0.20	77.08	0.60	21351	No
PE-11	Present Study	Airsoft Pellet	6.00	0.20	72.46	0.54	18940	No
PE-12	Present Study	Airsoft Pellet	6.00	0.20	87.36	0.78	27559	No
PE-13	Present Study	Paintball	17.30	3.21	67.06	7.21	30685	No
PE-14	Present Study	Paintball	17.30	3.19	100.21	16.00	68086	Yes
PE-15	Present Study	Paintball	17.30	3.19	101.94	16.59	70586	No
PE-16	Present Study	Paintball	17.30	3.19	103.29	17.03	72463	Yes
PE-17	Present Study	Paintball	17.30	3.20	111.00	19.72	83900	Yes
PE-18	Present Study	Airsoft Pellet	6.00	0.12	92.50	0.49	17491	No
PE-19	Present Study	Airsoft Pellet	6.00	0.12	115.63	0.77	27306	No
PE-20	Present Study	Paintball	17.30	3.19	68.01	7.38	31411	No
PE-21	Present Study	Paintball	17.30	3.06	95.58	13.98	59476	No
PE-22	Present Study	Paintball	17.30	3.20	109.46	19.15	81466	Yes
PE-23	Present Study	Paintball	17.30	3.16	108.94	18.74	79733	Yes
PE-24	Present Study	Airsoft Pellet	6.00	0.21	67.22	0.47	16483	No
PE-25	Present Study	Airsoft Pellet	6.00	0.20	84.02	0.71	25068	No
PE-26	Present Study	Paintball	17.30	3.14	66.81	7.00	29775	No
PE-27	Present Study	Paintball	17.30	3.21	100.55	16.24	69091	No
PE-28	Present Study	Paintball	17.30	3.19	114.08	20.75	88266	Yes
PE-29	Present Study	Paintball	17.30	3.17	106.38	17.96	76394	Yes
PE-30	Present Study	Paintball	17.30	3.20	109.69	19.25	81876	Yes
PE-31	Present Study	Paintball	17.30	3.21	106.38	18.17	77318	Yes
PE-32	Present Study	Paintball	17.30	3.19	101.75	16.50	70202	Yes
PE-33	Present Study	Airsoft Pellet	6.00	0.20	83.32	0.70	24873	No
PE-34	Present Study	Paintball	17.30	3.22	100.70	16.32	69420	Yes
PE-35	Present Study	Delrin Impactor	19.90	112.55	8.66	4.22	13583	No
PE-36	Present Study	Delrin Impactor	19.90	112.55	8.82	4.38	14079	No
PE-37	Present Study	Delrin Impactor	19.90	112.55	8.45	4.02	12914	No
PE-38	Present Study	Delrin Impactor	19.90	112.55	8.85	4.40	14163	No
PE-39	Present Study	Plastic Rod	7.62	0.35	5.68	0.01	122	No
PE-40	Present Study	Plastic Rod	7.62	0.35	15.46	0.04	904	No

Table 3 (cont.): Test results from experimental eye impact tests on porcine eyes.

Test	Author (Year)	Object	Projectile Diameter (mm)	Projectile Mass (g)	Projectile Velocity (m/s)	Kinetic Energy (J)	Normalized Energy (J/m^2)	Globe Rupture (Yes / No)
PE-41	Present Study	Plastic Rod	7.62	0.35	10.82	0.02	443	No
PE-42	Present Study	Foam	4.50	0.04	25.93	0.01	826	No
PE-43	Present Study	Foam	4.50	0.04	21.97	0.01	593	No
PE-44	Present Study	Foam	4.50	0.04	29.27	0.02	1052	No
PE-45	Present Study	Plastic Rod	7.62	0.35	13.44	0.03	683	No
PE-46	Present Study	Plastic Rod	7.62	0.35	19.63	0.07	1457	No
PE-47	Present Study	Foam	4.50	0.04	16.46	0.01	333	No
PE-48	Present Study	Foam	4.50	0.04	32.82	0.02	1323	No
PE-49	Present Study	Aluminum Rod	11.16	5.19	33.78	2.96	30250	No
PE-50	Present Study	Aluminum Rod	11.16	5.19	37.78	3.70	37840	No
PE-51	Present Study	Aluminum Rod	9.25	3.57	28.13	1.41	21051	No
PE-52	Present Study	Aluminum Rod	9.25	3.57	34.91	2.18	32421	No
PE-53	Present Study	BB	4.37	0.34	96.02	1.58	105151	No
PE-54	Present Study	BB	4.37	0.34	165.62	4.64	309787	Yes
PE-55	Present Study	BB	4.37	0.34	142.13	3.39	225981	Yes
PE-56	Present Study	Foam	4.50	0.04	149.63	0.41	26020	No
PE-57	Present Study	BB	4.37	0.34	139.96	3.33	222202	Yes
PE-58	Present Study	BB	4.37	0.34	139.96	3.34	222986	Yes
PE-59	Present Study	BB	4.37	0.34	99.74	1.70	113213	Yes
PE-60	Present Study	BB	4.37	0.34	98.13	1.64	109398	Yes
PE-61	Present Study	BB	4.37	0.34	95.93	1.54	102911	Yes
PE-62	Present Study	BB	4.37	0.34	99.28	1.69	112772	Yes
PE-63	Present Study	BB	4.37	0.34	98.20	1.64	109723	Yes
PE-64	Present Study	BB	4.37	0.34	97.59	1.63	108904	No
PE-65	Present Study	BB	4.37	0.34	131.74	2.96	197388	Yes

Table 4: Test results from experimental eye impact tests on human eyes.

Test	Author (Year)	Object	Projectile Diameter (mm)	Projectile Mass (g)	Projectile Velocity (m/s)	Kinetic Energy (J)	Normalized Energy (J/m^2)	Globe Rupture (Yes / No)
HE-1	Present Study	Airsoft Pellet	6.00	0.12	88.32	0.45	15987	No
HE-2	Present Study	Airsoft Pellet	6.00	0.12	91.62	0.50	17531	No
HE-3	Present Study	Airsoft Pellet	6.00	0.12	92.12	0.49	17364	No
HE-4	Present Study	Airsoft Pellet	6.00	0.12	117.80	0.80	28439	No
HE-5	Present Study	Paintball	17.30	3.20	71.73	8.24	35070	Yes
HE-6	Present Study	Paintball	17.30	3.20	71.28	8.14	34613	Yes
HE-7	Present Study	Airsoft Pellet	6.00	0.21	73.03	0.56	19694	No
HE-8	Present Study	Airsoft Pellet	6.00	0.20	76.29	0.57	20330	No
HE-9	Present Study	Airsoft Pellet	6.00	0.20	78.30	0.62	22032	No
HE-10	Present Study	Airsoft Pellet	6.00	0.20	85.33	0.74	26292	No
HE-11	Present Study	Paintball	17.30	3.13	65.50	6.72	28604	Yes
HE-12	Present Study	Paintball	17.30	3.21	71.10	8.10	34461	No
HE-13	Present Study	Paintball	17.30	3.19	97.88	15.29	65030	Yes
HE-14	Present Study	Airsoft Pellet	6.00	0.11	93.63	0.50	17798	No
HE-15	Present Study	Airsoft Pellet	6.00	0.12	109.74	0.71	24939	No
HE-16	Present Study	Paintball	17.30	3.19	68.02	7.37	31370	No
HE-17	Present Study	Paintball	17.30	3.21	73.28	8.61	36645	Yes
HE-18	Present Study	Airsoft Pellet	6.00	0.21	75.00	0.58	20591	No
HE-19	Present Study	Airsoft Pellet	6.00	0.21	87.35	0.79	27849	No
HE-20	Present Study	Paintball	17.30	3.22	71.10	8.13	34572	Yes
HE-21	Present Study	Paintball	17.30	3.19	70.77	8.00	34032	No
HE-22	Present Study	Paintball	17.30	3.20	107.17	18.36	78120	Yes
HE-23	Present Study	Paintball	17.30	3.21	75.29	9.09	38684	Yes

Table 4 (cont.): Test results from experimental eye impact tests on human eyes.

Test	Author (Year)	Object	Projectile Diameter (mm)	Projectile Mass (g)	Projectile Velocity (m/s)	Kinetic Energy (J)	Normalized Energy (J/m^2)	Globe Rupture (Yes / No)
HE-24	Present Study	Paintball	17.30	3.22	72.00	8.34	35478	Yes
HE-25	Present Study	Paintball	17.30	3.20	108.00	18.69	79493	Yes
HE-26	Present Study	Paintball	17.30	3.21	112.50	20.33	86503	Yes
HE-27	Present Study	Cork	30.00	9.48	8.86	0.37	527	No
HE-28	Present Study	Airsoft Pellet	6.00	0.21	81.19	0.68	23981	No
HE-29	Present Study	Airsoft Pellet	17.30	3.20	109.44	19.15	81471	Yes
HE-30	Present Study	Delrin Impactor	19.90	112.55	8.72	4.28	13761	No
HE-31	Present Study	Delrin Impactor	19.90	112.55	8.62	4.18	13435	No
HE-32	Present Study	Delrin Impactor	19.90	112.55	8.53	4.10	13167	No
HE-33	Present Study	Plastic Rod	7.62	0.35	23.50	0.10	2089	No
HE-34	Present Study	Plastic Rod	7.62	0.35	23.96	0.10	2171	No
HE-35	Present Study	Plastic Rod	9.75	0.69	20.16	0.14	1867	No
HE-36	Present Study	Plastic Rod	9.75	0.69	19.26	0.13	1704	No
HE-37	Present Study	Plastic Rod	7.62	0.35	23.75	0.10	2134	No
HE-38	Present Study	Plastic Rod	7.62	0.35	24.46	0.10	2264	No
HE-39	Present Study	Plastic Rod	9.75	0.69	19.23	0.13	1699	No
HE-40	Present Study	Plastic Rod	9.75	0.69	17.83	0.11	1460	No
HE-41	Present Study	Foam	4.50	0.04	45.73	0.04	2569	No
HE-42	Present Study	Foam	4.50	0.04	38.06	0.03	1780	No
HE-43	Present Study	Foam	4.50	0.04	44.66	0.04	2450	No
HE-44	Present Study	Foam	4.50	0.04	41.16	0.03	2081	No
HE-45	Present Study	Foam	4.50	0.04	47.23	0.04	2740	No
HE-46	Present Study	Foam	4.50	0.04	43.65	0.04	2341	No
HE-47	Present Study	BB	4.37	0.34	10.98	0.02	1370	No
HE-48	Present Study	BB	4.37	0.34	11.47	0.02	1496	No
HE-49	Present Study	BB	4.37	0.34	11.37	0.02	1469	No
HE-50	Present Study	BB	4.37	0.34	11.19	0.02	1425	No
HE-51	Present Study	BB	4.37	0.34	10.18	0.02	1179	No
HE-52	Present Study	Aluminum Rod	9.25	3.57	44.10	3.47	51752	Yes
HE-53	Present Study	Aluminum Rod	9.25	3.57	50.40	4.54	67585	Yes
HE-54	Present Study	Aluminum Rod	9.25	3.57	56.05	5.61	83594	Yes
HE-55	Present Study	Aluminum Rod	9.25	3.57	59.20	6.26	93255	Yes
HE-56	Present Study	Aluminum Rod	9.25	3.57	43.58	3.39	50531	Yes
HE-57	Present Study	Aluminum Rod	9.25	3.57	42.13	3.17	47227	Yes
HE-58	Present Study	Aluminum Rod	11.16	5.19	43.71	4.96	50646	Yes
HE-59	Present Study	Aluminum Rod	11.16	5.19	44.10	5.05	51557	Yes
HE-60	Present Study	Aluminum Rod	11.16	5.19	53.21	7.35	75075	Yes
HE-61	Present Study	Aluminum Rod	11.16	5.19	44.69	5.18	52958	Yes

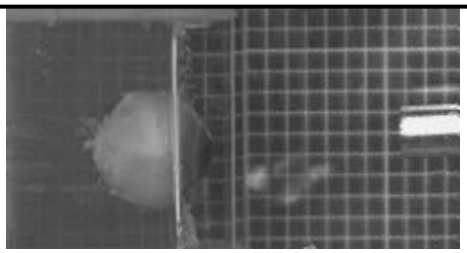
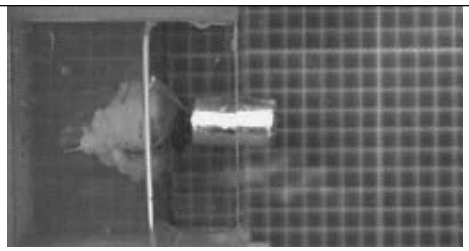
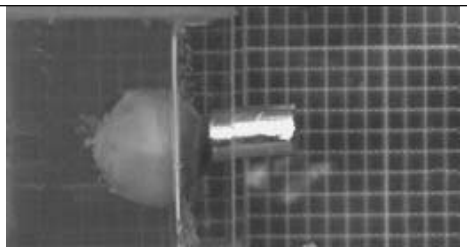
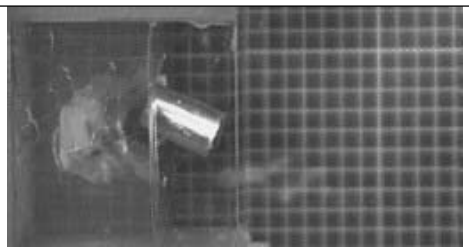
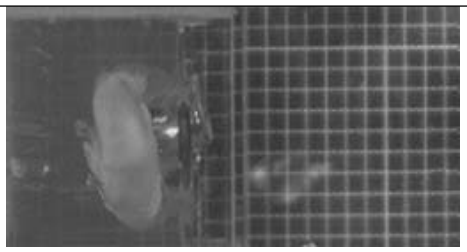
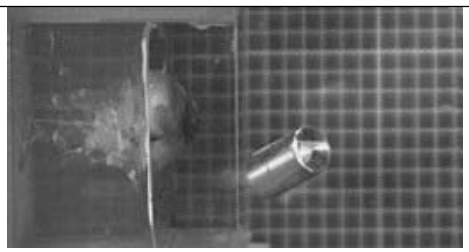
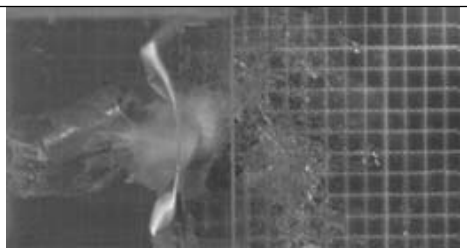
Time	Porcine Eye	Human Eye
0 ms		
1 ms		
2 ms		
Final		

Figure 3: Comparison of similar tests using porcine and human eyes using high speed video; the porcine eye did not rupture, while the human eye sustained a ruptured globe.

Part 3: Results of Data Analysis

Projectile characteristics of diameter, mass, velocity, kinetic energy, and normalized energy were evaluated by computing their significance and Goodman-Kruskal Gamma values. Logistic regression revealed that both kinetic energy and normalized energy were significant injury predictors for globe rupture, both porcine and human eyes ($p = 0.001$ for each) (Table 5). Similarly, the statistical analysis also showed that normalized energy presented the most statistically significant Goodman-Kruskal Gamma values for predicting globe rupture, with a value of 0.98 for normalized energy and human eyes, versus 0.87 for kinetic energy and human eyes (Table 6). Similar results were found for Goodman-Kruskal Gamma values for porcine eyes and normalized energy (0.96) and for kinetic energy (0.83). Other injury risk parameters of diameter, mass, and projectile velocity were not found to be as significant and did not yield as high of Goodman-Kruskal Gamma values.

The coefficients for the injury risk function were estimated for each dataset, human and porcine eyes (Table 7). These coefficients can be coupled with the equation given in Equation 2, to represent the risk of globe rupture based on measured parameters from projectiles striking the eye.

The risk functions for kinetic energy for both porcine and human eyes are calculated. A 50% risk of globe rupture for porcine eyes was found to be 11.1 J (Figure 4), as opposed to 8.7 J for human eyes (Figure 5).

The risk functions for normalized energy for both porcine and human eyes are calculated. A 50% risk of globe rupture for porcine eyes was found to be 71,145 J/m^2 (Figure 6), as opposed to 35,519 J/m^2 for human eyes (Figure 7).

For all predictors of eye injury, a logit analysis was performed to calculate the confidence intervals at 50% risk (Table 8). Enough data were present for each of the four different risk functions to fully estimate confidence intervals for each risk function.

Table 5: P-values for different projectile characteristics for predicting globe rupture.

	Projectile Diameter (mm)	**Projectile Mass (g)**	**Projectile Velocity (m/s)**	**Kinetic energy (J)**	**Normalized energy (J/m^2)**
Porcine Eyes	0.095	0.078	< 0.001	< 0.001	< 0.001
Human Eyes	0.146	0.263	< 0.001	0.001	< 0.001

Table 6: Goodman-Kruskal Gamma values for different projectile characteristics for predicting globe rupture.

	Projectile Diameter (mm)	**Projectile Mass (g)**	**Projectile Velocity (m/s)**	**Kinetic energy (J)**	**Normalized energy (J/m^2)**
Porcine Eyes	0.06	-0.23	0.90	0.83	0.96
Human Eyes	0.47	-0.75	0.55	0.87	0.98

Table 7: Injury risk function coefficients for globe rupture of both porcine and human eyes, using both kinetic and normalized energy. Standard errors for these parameters given in parenthesis.

	Kinetic energy (J)		**Normalized energy (J/m^2)**	
	Parameter "a"	*Parameter "b"*	*Parameter "a"*	*Parameter "b"*
Porcine Eyes	2.4416 (0.3987)	0.22071 (0.04436)	6.732 (1.675)	0.00009463 (0.00002380)
Human Eyes	1.2490 (0.3098)	0.14294 (0.05482)	9.123 (3.192)	0.00025684 (0.00009257)

Table 8: Confidence intervals for 50% risk of injury.

	Kinetic energy (J)			**Normalized energy (J/m^2)**		
	50% Risk	*Lower Bound*	*Upper Bound*	*50% Risk*	*Lower Bound*	*Upper Bound*
Porcine Eyes	11.1	8.6	14.8	71145	63245	80390
Human Eyes	8.7	5.5	19.1	35519	32018	40641

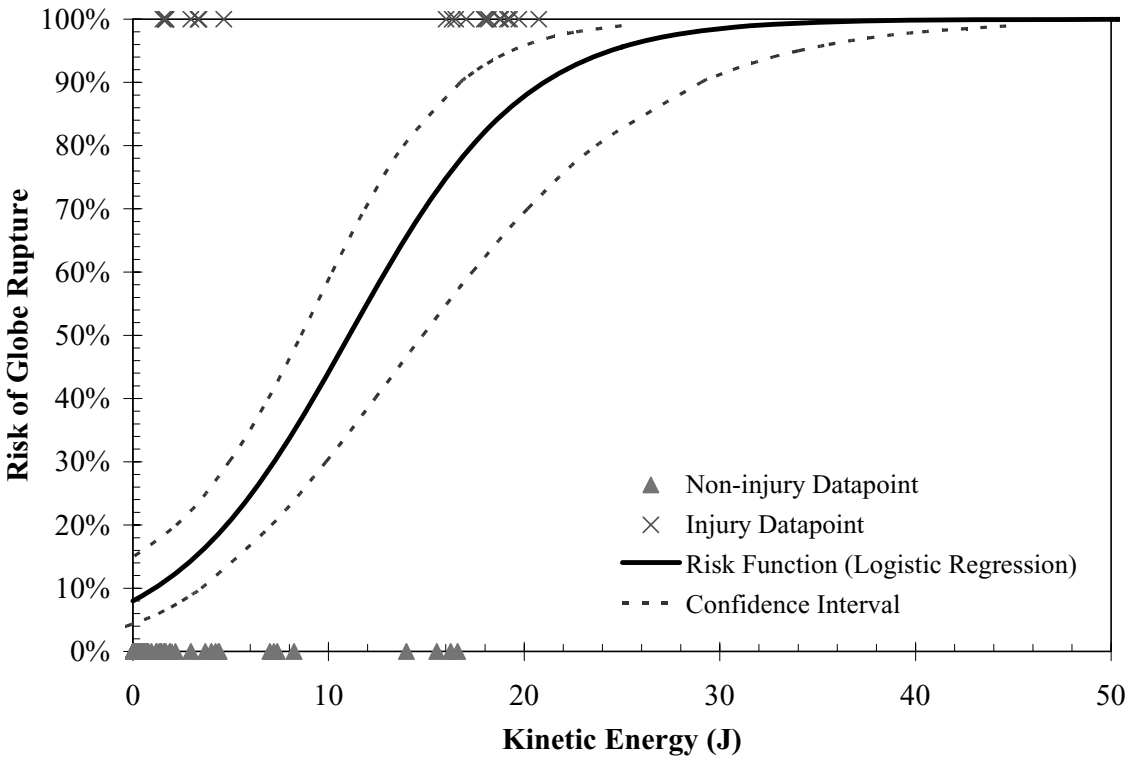


Figure 4: Injury risk curves for globe rupture of porcine eyes calculated from kinetic energy.

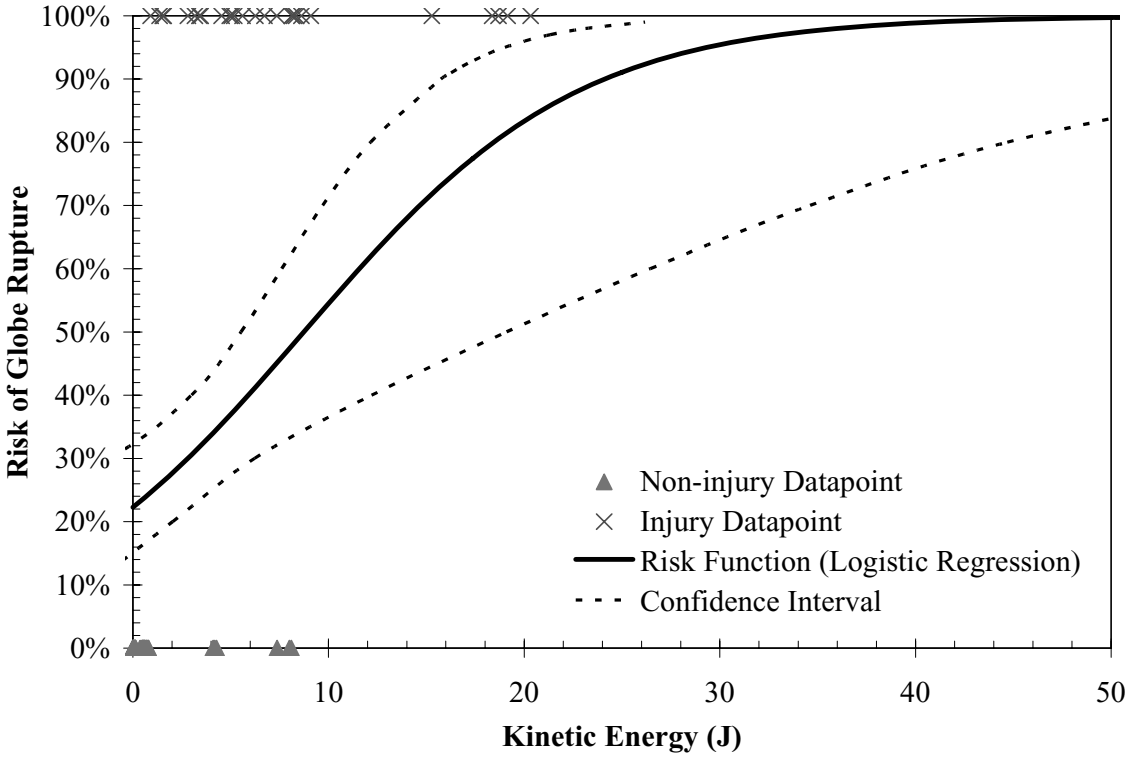


Figure 5: Injury risk curves for globe rupture of human eyes calculated from kinetic energy.

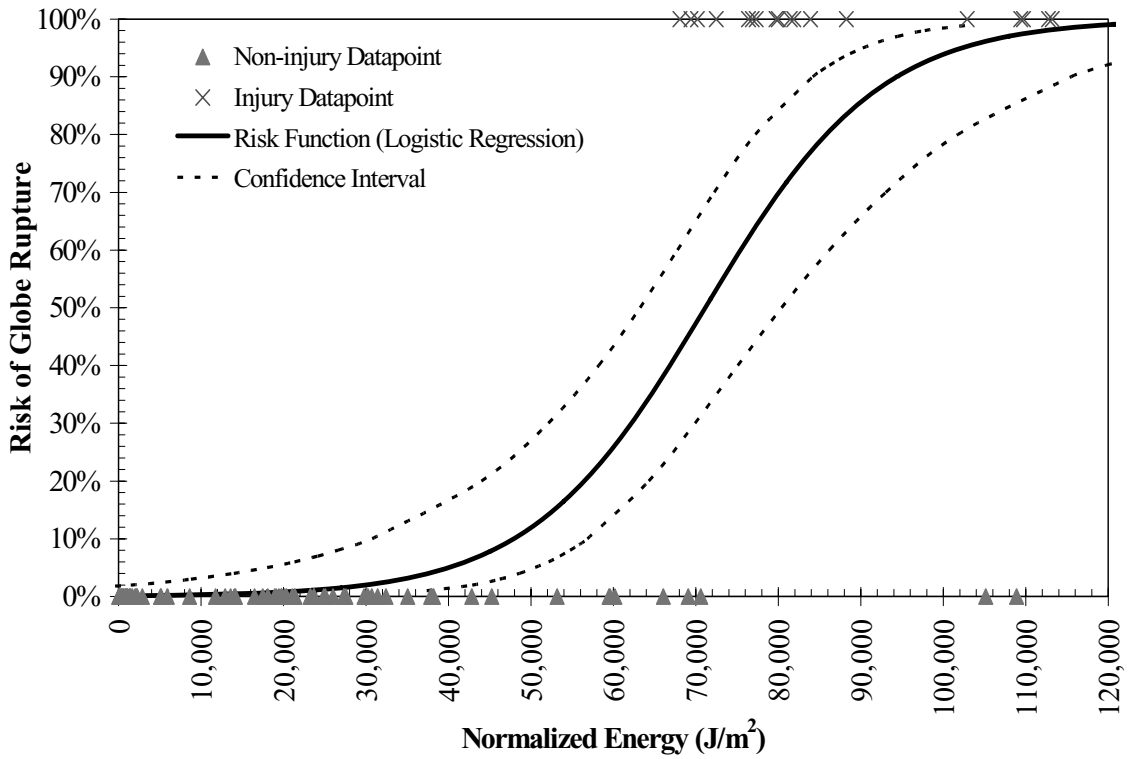


Figure 6: Injury risk curves for globe rupture of porcine eyes for normalized energy.

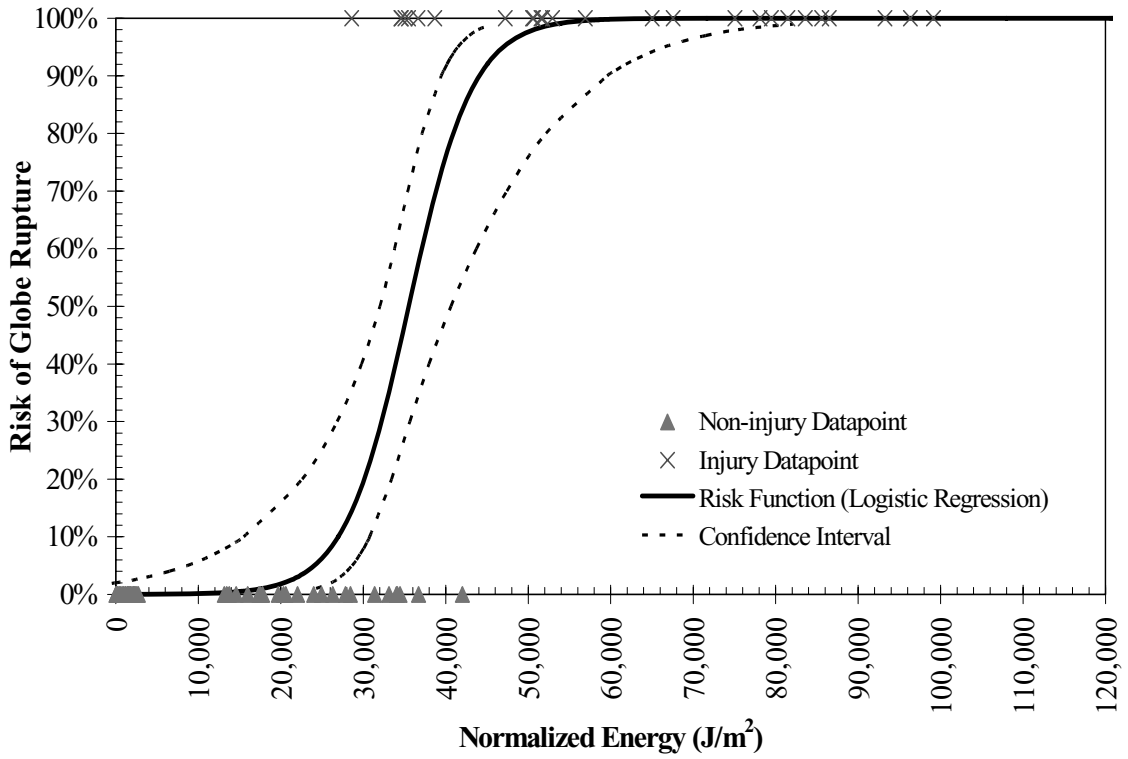


Figure 7: Injury risk curves for globe rupture of human eyes for normalized energy.

DISCUSSION

Binary Linear Regression vs. Other Injury Risk Functions

Other injury risk functions, such as the CT method, the modified median rank, and the certainty method, have been suggested because they offer a methodology to develop an injury risk function based strictly on the experimentally determined biomechanical data (Mertz 1996, Eppinger 1999, DiDomenico 2003, Kent 2004). In order to investigate the applicability of the logistic distribution and binary logistic regression, the injury risk function for human eyes is compared for these parametric and non-parametric methods (Figure 8). Comparing the injury risk functions, it can be observed that all methods predict a similar 50% risk of globe rupture, with the CT technique predicting a 50% risk at 34,572 J/m^2, the modified median rank at 35,310 J/m^2, and the certainty method at 35,000 J/m^2, compared to 35,519 J/m^2 from the logistic regression. Moreover, the certainty method risk curve lies within the 90% confidence interval of the logistic regression curve. The CT and the modified mean rank curves are almost completely within the boundaries.

Based on the overall similarity of these injury risk functions, it is felt that the best way of determining injury risk based on the data at hand is by the binary logistic regression injury risk function. Despite the amount of data used to generate the risk functions in this study, there is still a limited amount of data that is being used to represent a much larger population. The CT injury risk model shows a 0% risk of injury for all levels of input below the first injury point and a 100% risk of injury for all levels of input above the last non-injury datapoint (Kent 2004). It would be unlikely that both the first injury datapoint and the last non-injury datapoint determined in this study represented the exact extreme tolerances for the overall human population. The binary logistic regression, the modified median rank, and the certainty method reflect this limitation of the experimental data while closely matching the specific injury risk depicted from our exact experimental dataset.

The median rank method and certainty method have also been used to generate injury risk functions from biological data (Mertz 1996, Eppinger 1999). Both of these methods compare very favorably overall to the binary logistic regression risk function. However, the logistic regression analysis shows a strong goodness of fit with $p < 0.001$ and a Goodman-Kruskal Gamma value of 0.98. Due to its widespread acceptance and suitability for generating injury risk functions for biological data (Eppinger 1999, Kent 2004), the binary logistic regression is the recommended technique for generating the globe rupture injury risk function. While both the median rank and certainty methods are useful to validate the applicability of the logistic distribution and binary logistic regression analysis for this dataset, they are not the recommended final form of the injury risk function.

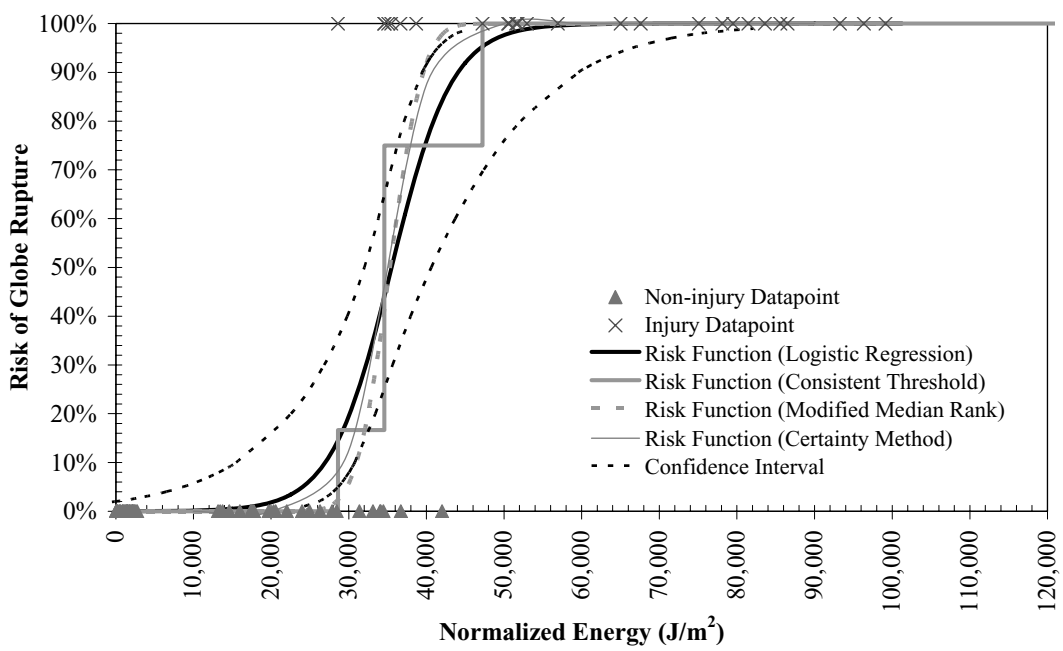


Figure 8: Comparison of binary logistic regression injury risk vs. consistent threshold, modified median rank, and certainty method injury risk for the prediction of globe rupture for human eyes based on normalized energy.

Kinetic Energy vs. Normalized Energy

Two types of parameters were used to generate injury risk functions for the prediction of globe rupture. The projectile's kinetic energy, accounts for both the mass and velocity of the assaulting object. Traditionally for eye injury prediction, the kinetic energy of the projectile is used to describe either a threshold for injury response, or has been used to generate injury risk functions to estimate the actual injury potential of an object (Duma 2000, Scott 2000). Kinetic energy has been proven to be related to eye injury response and much better than mass or velocity alone, since both a heavy but relatively slower moving particle and a lightweight, but relatively faster moving particle may, in fact, have the same injury potential. However, the measure of kinetic energy omits to reflect the actual physical size of the projectile, a parameter that is also highly correlated to injury response.

Normalized energy has been defined in this paper as the kinetic energy of a projectile divided by the projected area of the projectile. It could be said that the relationship of kinetic energy to normalized energy is analogous to the relationship of the force to its counterpart of stress. While stress reflects the amount of force acting over a given area, normalized energy reflects the amount of energy that is being presented to a given area of the eye. The projected area reflects the size of the projectile as it contacts the eye. Therefore, considering two objects with the same overall kinetic energy, the smaller projectile will, in turn, develop a higher normalized energy than the larger projectile. It has been experimentally shown in this study that this higher normalized energy directly correlates to a higher risk of globe rupture, and that normalized energy is a better predictor of injury than kinetic energy alone.

Normalized Energy vs. Material Stress

Due to the increase in use of computational models to study injury and predict when failure occurs, a comparison between the injury risk functions based on normalized energy and material stress predicted from computational models is warranted. Using results from previously conducted computational simulations (Stitzel 2002), the risk of globe rupture based on the normalized energy of the simulated projectile can be calculated and compared to overall peak stress levels generated in the computational model (Table 9).

Two BB impact simulations were previously reported by Stitzel et al. (2002). For a 56 m/s impact velocity, the model predicted a peak stress of 22.81 MPa, just under the estimated failure stress of 23 MPa. The same impact parameters results in a 59% predicted risk of globe rupture from the normalized energy risk function. For the higher velocity impact of 92 m/s, the computer model predicts globe rupture by exceeding the failure stress limit and the normalized energy injury risk function predicts a 100% risk of globe rupture.

Foam impacts to the eye were also simulated using the computer model, and both scenarios were far under the failure stress limit of 23 MPa, at 3.18 MPa and 7.83 MPa for 10 m/s and 30 m/s foam impacts, respectively. When comparing to the normalized energy injury risk functions, both impacts are predicted to have a less than 1% risk of globe rupture.

Table 9: Comparison of peak stress level from computational simulation to predicted injury risk from parametric injury risk function.

Simulation Number	Object	Velocity (m/s)	Normalized Energy (J/m^2)	Peak Stress (MPa)	Failure Stress (MPa)	Predicted Injury Risk
S1	BB	56.0	36971	22.81	23.00	59%
S2	BB	92.0	99784	32.76	23.00	100%
SF1	Foam	10.0	122	3.18	23.00	< 1%
SF2	Foam	30.0	1094	7.83	23.00	< 1%
SB1	Baseball	34.4	19057 *	22.15	23.00	1% *
SB2	Baseball	41.2	27336 *	24.62	23.00	11% *

* Because the baseball is larger in diameter than the eye, the amount of normalized energy presented to the eye is underpredicted, resulting in a low estimation of injury risk

Finally, two baseball impact simulations were compared to the normalized energy injury risk functions. Unfortunately this scenario shows that for objects larger than the diameter of the eye, using the normalized energy injury risk functions can be misleading. Because some of the energy is transmitted into the surrounding orbit in the computer simulation, not all of the energy from the model is actually transmitted to the eye. Additionally, the calculation for normalized energy assumes even distribution of energy across the entire projected area of the impacting object, when only a smaller local region of the baseball is actually interacting with the eye. This results in underestimating the actual normalized energy being transferred to the eye. With this in mind, the predicted risk of injury of simulated 34.4 m/s and 41.2 m/s impacts is shown to be 1% and 11%, respectively. However, normalizing the energy only over the projected area of the eye (assumed 25 mm in diameter) the predicted injury risk for both scenarios is predicted to be 100%.

Given the increased use of computational models to study injuries and the paucity of data for dynamic material properties of the human eye, comparisons between the experimentally determined injury risk functions and the results of computational simulations should be made. A future area of research should be to further correlate all of the impact scenarios reported in this paper to the predicted injury risk from computational simulations. At present, using only limited comparisons, high injury risk (> 59%) is predicted as the material stresses from the finite element simulations approach their assumed material failure stresses.

Outlier Data Points

It should be noted that there are two high level non-injurious datapoints for the porcine eye injury risk functions using normalized energy (Figure 6). These two datapoints were both the result of non-injurious BB impact tests on porcine eyes that appear to be unusually strong compared to the rest of the test specimens. Given the analysis of 183 individual eye impact tests, it is expected that some unusually strong or weak eyes would be tested. While these two particular outliers skew the shape of the normalized energy, porcine globe rupture risk curve, they also do not appreciably affect the 50% risk value that was calculated to be 71,145 J/m^2, as opposed to 68,815 J/m^2, if these datapoints were omitted from the logistic regression analysis (Figure 9). If estimation of injury risk at other normalized energy levels is desired, then it may be warranted that further analysis of risk using an analysis that omits these two datapoints may be additionally conducted.

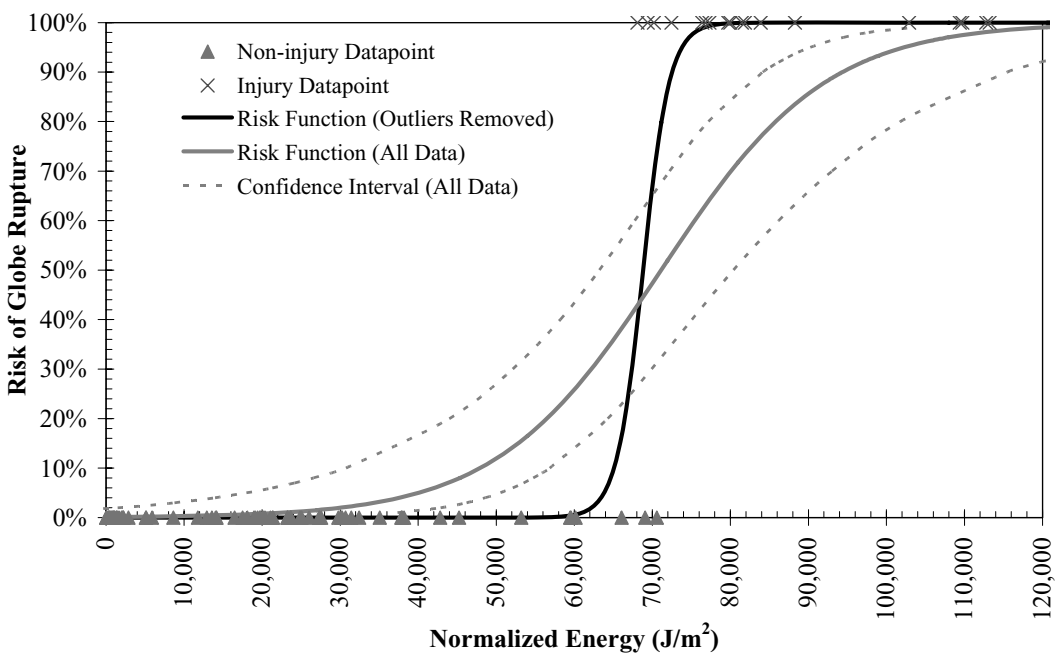


Figure 9: Comparison of injury risk functions for globe rupture of porcine eyes using normalized energy. The injury risk functions are generated using two methods: 1) using all data points and 2) excluding the two non-injury outlier datapoints. The confidence intervals shown are generated using all datapoints.

Human vs. Porcine Eye Strength

Given their relative geometric and anatomical similarities, porcine eyes have frequently been used as surrogates for human eyes for eye injury impact testing (Weidenthal 1966, Vinger 1997, Duma 2000, Scott 2000). The results of this study indicate that porcine eyes are appreciably stronger than human eyes. Using normalized energy, a 50% risk of globe rupture for porcine eyes was determined to be 71,145 J/m^2, as opposed to 35,519 J/m^2, for human eyes. This is almost exactly a 100% relative increase in strength in corneo-scleral strength for porcine eyes compared to human eyes.

In a previous study to determine the rupture pressures of eyes due to an increase in internal pressure, statistically significant differences were observed between human and porcine eyes under both static and dynamic loading conditions (Kennedy 2004). In this study, human and porcine eyes were subjected to increased internal pressure at both dynamic and quasi-static loading rates via pressurization through the optic nerve. Under static conditions porcine eyes were nearly 3 times stronger than human eyes, rupturing at 1.00 ± 0.18 MPa compared to 0.36 ± 0.20 MPa for human eyes. Dynamic loading again showed porcine eyes to be stronger at rupture pressures of 1.64 ± 0.32 MPa, compared to the rupture pressure of human eyes of 0.91 ± 0.29 MPa.

While no known studies have been reported that compare the material properties of human and porcine corneo-scleral tissue, studies have reported an increase in thickness of porcine scleral thickness relative to human sclera (Olsen 1998, Olsen 2002). These histological studies show that the nominal thickness of porcine sclera can be up to approximately two times greater than the thickness of human sclera. This increase in relative thickness could explain the increased tolerance for globe rupture for porcine eyes versus the human eye; however, to fully understand this issue an area of future research is the characterization of material properties of both human and porcine sclera at dynamic rates.

Coupled with the results of previous studies, the results of this research show that caution must be exercised when evaluating the outcome of experimental tests conducted using porcine eyes. Most experimental eye impact tests on post-mortem eyes are conducted for the purposes of determining if globe rupture or corneal-scleral penetration will occur. This study shows that porcine eyes are nearly twice as resistant to these types of injuries as human eyes. Therefore, a lack of pathology of globe rupture on a porcine eye will not necessarily indicate that a human eye will have negative pathology as well. In this case, the use of the injury risk functions provided in this paper will allow for a more accurate assessment of the potential for injury.

Post-mortem Tissue Degradation

It should be noted that all eyes used for experimental testing as part of this study were enucleated within 24 hours of death, stored in a saline soaked gauze wrap, and refrigerated until just prior to testing. For testing, the eyes were removed from refrigeration and kept hydrated as they returned to room temperature just prior to the actual testing. All eyes were tested within 180 days of death, with most eyes tested within 1 month of death. Other studies have been shown that using similar storage protocol, the number of days after death prior to testing is not correlated with the overall integrity of the corneo-scleral shell with an R^2 value of 0.14 (Kennedy 2004). This is because of the acellular makeup of the corneo-scleral shell. The strength of the eye comes from the collagen fibers similar to those found in ligaments. These tissues break down very slowly if kept hydrated and refrigerated. Also, the tissue was never frozen because it is sensitive to freeze-thaw cycles. Since the tissue was never frozen and was stored in refrigerated saline, the integrity of the globe was maintained prior to testing.

Combined Injury Risk Functions

The injury risk functions developed in this study can be combined with the similarly developed injury risk functions for other less severe eye injuries (Duma 2005). Using the injury risk functions reported in the previous study, combined with additional data generated during this study, injury risk functions can be compared for corneal abrasion, hyphema, lens dislocation, retinal detachment, and globe rupture.

Using normalized energy, a 50% injury risk of corneal abrasion, hyphema, lens dislocation, retinal damage, and globe rupture is found to be 1,503 J/m^2, 20,188 J/m^2, 19,194 J/m^2, 30,531 J/m^2, and 35,519 J/m^2, respectively. Overall, the results of this combined set of injury risk functions appear logical. Generally, the injury pathologies that are seen more frequently in the clinical setting occur at lower energies than the injury pathologies that are of higher severities and less frequently observed (Pearlman 2001, Kuhn 1995, Duma 1996). Pearlman et al. (2001) reviewed 263 cases of eye injury from automobile accidents and observed corneal abrasion and hyphema to be the two most frequently occurring eye injury types in auto accidents. In a review of 24

cases, Kuhn et al. (1995) found corneal abrasion and hyphema to occur in approximately 33% of automotive eye injury cases, compared to approximately 16% who suffered retinal injury. The study did not mention the incidence rate for lens dislocation and globe rupture was not observed in this study. Duma et al. (1996) show similar injury rates for corneal abrasion, hyphema, and retinal detachment, while showing approximately a 4% chance of globe rupture due to airbag-related eye trauma.

Future Applications

Currently, eye injury assessment tools for automobile, consumer product, sports, and military are not based on biomechanically determined injury limits. For automobile safety, anthropometric test devices (ATDs) such as the Hybrid-III dummy have no capability for measuring eye injury risk. The THOR dummy, utilizes four facial load cells to predict facial injury, but has no eye injury assessment capability. Conversely, the National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform and the American National Standards Institute (ANSI) Alderson headform have detailed facial geometry including the eyes, nose, and mouth, but no instrumentation to determine eye or other head injury. Due to the lack of appropriate measurement capabilities of these headforms, it is expected that the injury risk functions presented in this paper could serve to assess the eye injury risk from potential eye impacts. However, this is only possible in cases where the specific velocity and size of impacting projectiles can be determined.

Since the injury risk functions presented in this paper are input based, they could be useful in development of a biofidelic sensor and injury thresholds for a synthetic eye sensor. Projectile tests can be conducted on an instrumented synthetic eye and the sensor outputs calibrated to the predicted injury risk based on the input parameters. This has the approach to injury threshold determination for ATDs may ultimately yield more accurate injury risk prediction due to the fact that a direct mapping from input energy and known injury risk are correlated to sensor output. A development such as a synthetic eye in an advanced ATD headform would allow experimental testing and evaluation of possible eye injury hazards, even in scenarios such as automobile crash testing where it may be extremely difficult to isolate and determine projectile characteristics that may assault the eye.

Limitations

Despite the fact that the present study utilizes a large amount of experimental data for the development of injury risk functions, there are several areas where further research is warranted. First, while all experimental data was pooled into two large impact databases for human and porcine eyes, it is also possible to develop projectile specific risk functions for globe rupture and compare these to the overall injury risk functions. However, due to the large variety of objects used in the eye impact tests, an insufficient number of injury and non-injury data exists from which projectile specific injury risk functions can be determined. While it would have been possible to utilize a smaller variety of projectiles for the experimental tests, it was felt that this would negate the advantage of a sufficient variety of objects used to develop a versatile risk function for virtually any type of blunt projectile. Second, because of the rapid degradation of other internal structures of the eye, such as the retina and lens detaching from their in-vivo positions, it is not possible to test post-mortem eyes for injury pathologies such as lens and retinal damage. Third, due to the lack of cardiovascular pressure, it is not possible to test post-mortem eyes for hyphema. A limited amount of experimental data exists for these injuries from previously performed live animal tests. It would be desirable to have additional data in order to develop injury risk functions in a similar manner to that of the current study.

Although the current study demonstrates a clear and accurate method for determining the risk of globe rupture based on projectile characteristics, it has not presented a more typical set of experimental results of failure stress or failure strain of the corneo-scleral shell. At present, no studies have presented the failure stress or strain of the human eye due to dynamic impact. While the injury risk functions are useful in a practical sense, it is still desirable to determine these properties of the human eye, especially for use in computational models of the eye. Knowledge of the material properties of the human and the porcine eye will also have a profound effect in explaining the significant strength differences between human and porcine eyes.

CONCLUSION

Eye injuries in both the civilian and military sectors are severely debilitating and pose an enormous health cost. The relative severity of eye injuries is much greater for the military than in the civilian population. Computer models have been shown to be an effective tool in predicting eye injury response, such as globe rupture, from blunt impact. However, the use of computer models is not always practical or possible for the wide range of impact scenarios or industries in which eye injuries are a concern. Also, due to a lack of instrumentation, the prediction of eye injuries using anthropomorphic test devices is not currently possible. The current study presents a new method to determine the risk of globe rupture to projectile impacts, based on the projectile characteristics of mass, velocity, and area of contact. A total of 183 eye impact tests were analyzed to develop injury risk functions and estimate confidence intervals for human and porcine eyes. It has been shown that porcine eyes are more resistant to globe rupture than human eyes. In the present study, a 50% risk of globe rupture was found to be 71,145 J/m^2 for porcine eyes, compared to 35,519 J/m^2 for human eyes. The results presented in this paper will be useful in estimating the risk of globe rupture when projectile parameters are known, or can be coupled with a computational or physical model for injury risk criteria that correlates with experimentally based injury response.

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