EFFECTIVENESS OF COLLISION-INVOLVED MOTORCYCLE HELMETS IN THAILAND

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ABSTRACT

The purpose of this study was to analyze variables present in selected motorcycle crashes involving helmeted riders to find the best injury predictors. The helmets used in this study were collected from motorcycle crashes in Thailand. Pertinent data were collected, a conventional helmet impact drop test apparatus was used to quantify the head impact forces, and stepwise multiple regression analyses were performed. The results indicate that the geometry of the object impacting the head and GSI were the best predictors for MAIS (R^2=.875) while geometry of the object, liner thickness and impact energy were the best predictors for ISS (R^2=.911).

Analysis of motor vehicle crashes in the United States in the year 2001 reveals that motorcyclist fatalities increased 7.2%, from 2,862 fatalities in 2000 to 3,067 in 2001 [NHTSA 2002]. In 2001, 59,000 motorcyclists were injured, which represents an increase of 2.0% from 2000. These statistics are indicative of the risk that motorcycle riders face in the traffic environment and warrant the need for further research focusing on injury potential in motorcycle crashes.

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HELMET EFFECTIVENESS - According to the National Highway Traffic Safety Administration [NHTSA 2000], helmets are approximately 29% effective in preventing fatal head/brain injuries and 67% effective in preventing head/brain injuries to motorcyclists involved in traffic crashes. In 2000, motorcycle helmets saved an estimated 631 lives in the United States and could have saved an additional 382 lives if unhelmeted riders had worn a helmet [NHTSA 2000].

Head injuries are a significant concern for the collision-involved motorcyclist due to their debilitating and potentially life-threatening nature. However, a motorcyclist can be protected from these injuries by wearing a helmet [Hurt et al. 1981]. As evidenced by the above referenced statistics, the presence of a helmet can significantly alter the frequency and severity of head injuries [Hurt and Thom, 1992]. A typical motorcycle helmet shell and liner provide load distribution and energy absorption upon impact; therefore head injury outcome can be affected by the presence of a helmet [Newman 1993; Thom and Hurt 1993; Thom et al. 1995].

Observable helmet damage is not an idication of head injury. In different cases with different crash circumstances, it is possible for a helmet to be significantly damaged and no head injury will be present because the helmet provided adequate protection. Conversely, it is possible for helmeted individuals involved in collisions to sustain an injury to the head area without observable helmet damage. This study provides an analysis of helmet effectiveness using collision-involved helmets, where a significant head/helmet impact was known.

HELMET DAMAGE REPLICATION - For years, helmet damage replication drop tests have been used to evaluate helmet effectiveness and head impact severity [Hurt et al. 1976; Hurt and Thom 1985; Smith et al. 1993]. Governmental standards are also based on helmet performance during drop tests [US DOT 2000a, b; Thailand DOH 1996].

At the present time, typical measures and calculations collected from the drop tests include drop height, peak acceleration, impact duration, impact velocity, impact energy, Head Injury Criteria (HIC) and Gadd Severity Index (GSI). GSI and HIC have been developed as the two principal criteria for analyzing brain injury [SAE 1986]. Both criteria are computed from weighted acceleration data and theoretically derive a severity index value that considers both impact duration and the magnitude of head acceleration. Historically, HIC has been a controversial topic and it may have limited value in terms of evaluating helmet performance [Newman 1975].

The purpose of this study was to analyze the different variables present in motorcycle crashes involving helmeted riders, where significant helmet damage was present and significant head impact was known, to find the best predictors of injury outcome. Part of this process involved analysis of crash data obtained from in-depth motorcycle crash investigations conducted in Thailand.

THE THAILAND STUDY - In Thailand, motorcycles are the only form of transportation for many individuals and make up about 30% of vehicular traffic [Kasantikul 2001a, b; 2002]. In the streets of Bangkok, Thailand, traffic can become very congested and high numbers of motorcycles routinely weave in and out of traffic (Figure 1). Helmet use is mandatory in Thailand. Helmet usage rate, however, varies significantly between urban and rural areas. In urban areas, the usage rate is approximately 67% for motorcycle riders (i.e. the operator/driver of the motorcycle) and 30% for passengers (i.e. passive motorcycle occupants). In rural areas, the usage rate drastically declines to 22% for riders and 4% for passengers [Kasantikul 2001a, b]. Given its relatively high motorcycle/occupant vehicle ratio, Thailand is a "prime" location for studying motorcyclist head impacts and injury patterns.

In Thailand, data were gathered for 1082 motorcycle crashes over the three-year period during which the project was funded. A total of 723 on-scene, in-depth motorcycle collisions were investigated in Bangkok during 1998 and 1999. A total of 359 on-scene, in-depth accident-involved motorcycles were investigated in five more rural provinces in the year 2000.

The 1082 motorcycle crashes do not represent all motorcycle crashes in Thailand over that three-year period, they are the total number of crashes investigated and documented by the trained Thai crash investigation team based on the their physical location and resources at the time of the motorcycle collision. All the investigated crashes did not result in significant somatic or head injury and the crashes were not investigated based on any particular criterion (e.g. presence of a head injury).

Detailed investigations for each case were conducted by Thai investigators who were specifically trained in crash investigation. During the data collection period, investigators received notification of the motorcycle crashes via the emergency response system and were usually at the scene of the collision within 30 minutes of notification. At the crash scene, investigators documented physical evidence and often collected helmets worn/not worn by the motorcyclists. When all these data had been gathered, all 1082 motorcycle crashes were reconstructed and a range of crash speeds were calculated using published motorcycle collision reconstruction techniques [Fricke and Riley 1990; Severy et al. 1970]. All motorcyclist injuries were documented in Thailand and coded by a trained medical professional using the AIS-90 coding system [AAAM 1990]. Smith et al [2001] provides a complete and thorough description of the investigative methodology, which was performed using the Hurt study as a model [Hurt 1981]. The final report detailing the entire Thailand motorcycle crash investigation project and results was completed by Kasantikul in 2001.

Figure 1 – Motorcycle traffic in Bangkok, Thailand.

METHODS

Evaluating helmet effectiveness and identifying predictors of both head and overall injury potential first required identification of collision-involved helmets where a significant head impact was known. Following identification of acceptable cases, investigation information was recorded, detailed examination of the collision-involved helmet was conducted, and replication testing was performed. Finally, statistical analysis was conducted.

ANALYSIS OF THAILAND INVESTIGATION DATA – Out of the 220 total helmets collected in Thailand, 15 helmets were chosen for this study because they exhibited significant visible and replicable damage as well as the data pertinent for the chosen statistical analysis. A large amount of all the helmets collected in Thailand were not damaged therefore, only a smaller percentage of the total helmet sample exhibited visible and measurable damage. The 15 helmets chosen for this study were a subset of that smaller percentage of damaged helmets. Information regarding crash configuration, motorcycle impact speed, helmet impact surface, geometry of the object struck by the helmet, helmet ejection information, and AIS coded injuries were documented.

Head Maximum AIS (MAIS), which is the highest single head/brain AIS injury (AIS section 1 only) for an individual, was recorded and ISS scores were calculated for the 15 collision-involved motorcyclists. The Injury Severity Score (ISS) is derived from the AIS values to describe the overall magnitude of multiple injuries [Baker et al. 1974].

HELMET EXAMINATION - Helmets were selected for the current study only if significant head impact was known, the helmet damage could be replicated, the helmet remained on the rider/passenger's head throughout the crash sequence (i.e. the helmet was not "ejected"), and the variables needed for regression analysis were present in the investigation information. Typical signs of helmet/head impact include compression of the polystyrene liner and abrasions to the outer shell (Figure 2).

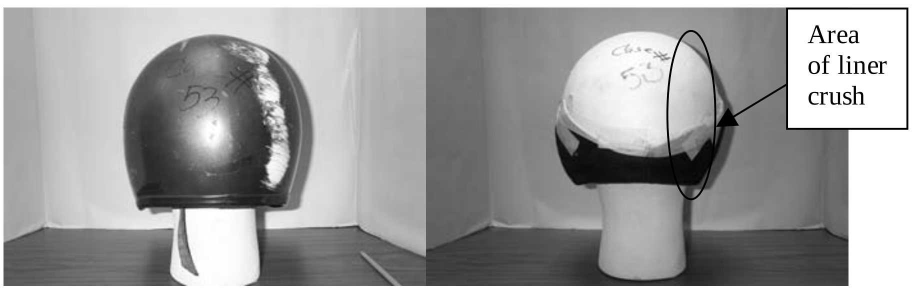

Figure 2 – Helmet shell abrasions and liner compression

Once a helmet was identified for inclusion in this study, it was disassembled and the shell and liner damage was examined, photographed and measured. The area and depth of liner crush damage were measured on each helmet. A direct measurement of maximum liner compression was taken with reference the "mirror image" location on the other side of the helmet. Helmet damage was documented from a 1 to 12 o'clock clock face (top view) direction and principal direction of force was estimated based on the damage patterns, magnitude and area of liner crush, motorcycle crash circumstances, and documented contact surfaces. Physical characteristics of the helmet including liner material, shell material, liner thickness, shell thickness, retention system operation, and weight were also documented.

HELMET SAMPLE – Descriptive statistics for the subject samples compared to all the collected Thai helmets are shown in Table 1. The liner material for all the Thailand helmets was EPS (Expanded Polystyrene). However, the 15 Thailand cases varied noticably in terms of crash configuration, impact speed, and impact surface.

Table 1 – Helmet sample data (Fiberglass = FG, Polycarbonate = PC, Acrylonitrile Butadiene Styrene = ABS, Polyethylene= PE)

	Liner Thickness (mm)	Shell Material	Shell Thickness (mm)	Rider (R) v. Passenger (P) Helmets
Subject Helmets (N=15)	Mean=20.6 SD=4.7	FG=6.6% PC=0.0% ABS=46.7% PE=46.7%	Mean=.97 SD=.15	R=93% P=7%
All Thai Helmets (N=220)	Mean=21.3 SD=6.8	FG=2.0% PC=17.0% ABS=43.0% PE=38.0%	Mean=1.02 SD=.41	R=90% P=10%

HELMET EXAMINATION AND DAMAGE REPLICATION - Replicating the damage measured on the impacted case helmet consisted of using an undamaged exemplar helmet from the remaining sample of Thailand helmets. Since most of the helmets were of the same common design and typically from the same manufacturer, locating an exemplar helmet was not a significant problem. The exemplar helmets were the same model and manufacturer as the collision-involved helmets and were undamaged (i.e. from a non-head-impact collision). Before exemplars were chosen for damage replication, it was verified that the collisions from which the exemplar helmets were chosen did not involve a significant helmet impact, which would compromise the integrity of the helmet. Exemplars also had the same shell material, the same liner density, and same mass as the collision-involved helmets. The exemplar helmets were thoroughly inspected and measured to verify that there was no damage present on the helmet, which was not observable with the naked eye.

The presence of EPS liners in all the 220 Thailand helmets was advantageous. EPS leaves a characteristic impact signature because it is “crushable” and does not completely rebound to its original shape. Therefore, any significant loss of the helmet liner’s ability to absorb force can be observed and measured. Any micro-structural deviations in the helmet materials that could not be directly measured were considered negligible.

For the present study, linear headform accelerations were analyzed using a uni-axial (Z-direction) accelerometer (Endevco Model 7701A), which was located at the CG of the headform assembly. The accelerometer signal was sampled at a rate of 10,000 Hz, in accordance with SAE J211 (1995). An appropriately sized ISO headform [ISO 1983] was mounted on a twin-wire drop test apparatus and acceleration data were collected using a PC-based data acquisition system (National Instruments). An infrared beam velocimeter system (GHI Systems) was used to record impact velocity.

Selection of the replication impact surface was based on the Thailand case information, crash scene photos, and the damage pattern for each helmet. The impact surfaces for the 15 collision-involved helmets varied from asphalt to sharp-edged metal. Each exemplar helmet was oriented to replicate the direction of the forces which were applied to the helmeted head and raised to a drop height that was predicted to impart the same amount of impact energy to the exemplar helmet as seen on the damaged collision-involved helmet. The helmet was released into free-fall and subsequently impacted the chosen surface.

Following impact, the digitized signal was calibrated, all bias was removed, and the signal was filtered digitally using an analog SAE Class 1000 low-pass filter. A custom software package (Biokinetics and Associates, Ltd.) then calculated and reported peak headform acceleration, impact velocity, impact energy, HIC, GSI and plotted the acceleration-time curve for each trial.

Following test impact, the exemplar helmet was removed from the headform and inspected and measured for damage. Comparison was made to the collision-involved helmet to confirm accurate damage replication. Measurements were taken for maximum liner deformation and liner crush area. If the exemplar helmet liner crush depth and impact area were not each within 10% of the original damage, testing was repeated using a different exemplar helmet, from a different drop height. If both the exemplar helmet crush area and depth were each within 10% of the collision-involved helmet damage, then the damage was determined to be adequately replicated for the purposes of this study. Similar methodology has been employed by previous researchers in studies involving replication of damage to collision-involved helmets [Smith et al 1993]. The drop tests yielded data including impact velocity, impact energy, peak headform acceleration, HIC, and GSI. Table 2 depicts the replication test data and impact surfaces. The cases are listed according to injury score and fatality is noted.

Table 2 – Case and exemplar helmet crush data

MAIS-ISS score	Impact Velocity (m/s)	Impact Energy (J)	Peak G's	HIC	GSI	Exemplar Helmet Impact Surface (model predictor)
0-2 (non-fatal)	3.37	28.39	50.52	111	121	Pavement (flat)
0-2 (non-fatal)	4.74	56.17	178.38	419	545	Pavement (flat)
0-3 (non-fatal)	6.09	92.72	252.70	1765	2108	Pavement (flat)
0-3 (non-fatal)	4.52	51.08	323.13	1122	1735	Flat Metal (flat)
0-3 (non-fatal)	5.94	88.21	188.08	1237	1439	Pavement (flat)
0-3 (non-fatal)	5.66	80.09	148.85	690	830	Pavement (flat)
0-3 (non-fatal)	3.32	27.56	36.43	51	59	Pavement (flat)
0-3 (non-fatal)	6.20	96.10	129.30	553	640	Pavement (flat)
1-38 (fatal)	4.79	57.36	203.30	695	939	Flat Metal (flat)
3-54 (fatal)	4.35	47.31	299.79	649	1233	Curb Anvil (blunt)
4-18 (fatal)	3.44	29.58	183.66	361	526	Hazard Anvil (sharp edge)
4-29 (fatal)	5.07	64.26	765.34	1585	6966	Cylinder Anvil (blunt)
4-41 (fatal)	5.67	80.37	322.02	1389	1869	Curb Anvil (blunt)
4-50 (fatal)	5.36	71.82	122.00	436	348	Hazard Anvil (sharp edge)
4-66 (fatal)	4.33	46.87	703.85	1442	5094	Hazard Anvil (sharp edge)

INJURIES - Of the 15 motorcyclists, 8 received nonfatal injuries and 7 received fatal injuries. For the 15 crashes, there were 4 cases where the rider did not part from the vehicle following the collision (3 fatal and 1 nonfatal), 4 cases where the rider departed from the vehicle following the collision (2 fatal and 2 nonfatal), and

7 cases where the motorcycle was deflected and the motorcyclist did not depart from his/her original riding position (2 fatal and 5 nonfatal). Appendix A lists all AIS coded injuries and the crash speeds for the 15 motorcyclists. Figure 3 shows one of the fatal cases selected for this study. It involves, a motorcycle rider who collided with the rear-end of a parked truck. The rider's helmet/head contacted a sharp metal edge on the rear of the truck and he sustained fatal injuries.

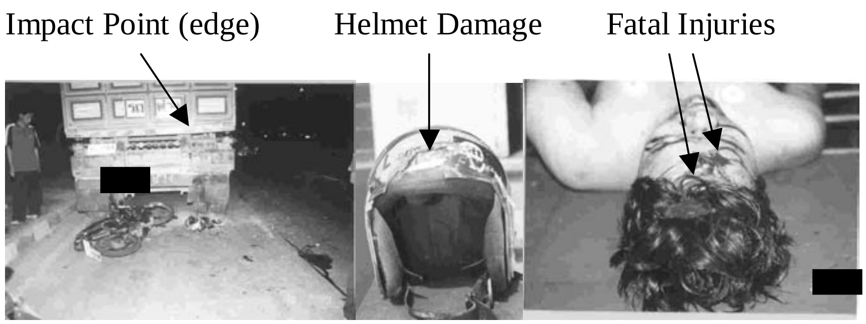

Figure 3 – The parked truck, helmet damage, and fatal head injuries

STATISTICAL ANALYSIS - The data collected and recorded were statistically analyzed using SPSS Version 11.0 (Chicago, IL). Two separate stepwise multiple regression analyses were used to find predictors of head MAIS and ISS based on 12 independent variables. The independent variables were helmet mass, maximum helmet liner crush, area of liner deformation, helmet liner thickness, helmet shell thickness, shell material, head impact surface, geometry of the object struck, peak headform impact acceleration, impact energy, HIC values and GSI values.

Variables chosen to be included in the model were helmet characteristics that could be directly measured, laboratory data, and physical evidence from the scene of the collision. These variables were chosen based on consultation with the Thailand investigators and staff of the Head Protection Research Lab, who have extensive helmet testing and head injury analysis experience.

In the stepwise multiple regression, SPSS produces a series of equations, first a bivariate solution, then additional equations in a step-by-step order as other independent variables enter the multiple regression solution. The final stepwise equation will be the same as the single equation produced by standard multiple regression if the same set of predictor variables is used. Stepwise regression offers the advantage of listing the order of the steps in the development of the equation so that the effect of each variable can be identified as it enters the equation. Criterion for entry into the regression model was $p < .05$.

RESULTS

THAILAND CASE DATA: ENVIRONMENTAL CONTACT SURFACE - Pavement was found to be the most common environmental contact surface for riders and passengers. A "rider" is the operator/driver of the motorcycle and a "passenger" is a non-operator/passive occupant. Riders and passengers were injured by striking the pavement in more than 80% of the investigated cases. This high frequency makes fundamental sense, since the majority of motorcycle riding occurs on pavement and riders will often end up on the pavement, unless they travel off the roadway or become entangled with a vehicle or other environmental object (e.g., tree, post, or pole). Table 3 depicts the distribution of the environment contact surfaces for the 1082 investigated motorcycle crashes in Thailand. It was possible to code multiple contact surfaces in an individual crash.

Table 3 – Environmental Contact Surface

Environment Contact Surfaces	Frequency	Percent
Asphalt pavement	1591	51.3
Concrete pavement	915	29.5
Concrete pole or post	94	3.0
Concrete barrier, guard rail	21	0.7
Concrete curb	120	3.9
Gravel, soil pavement	42	1.4
Gravel, soil unpaved shoulder	40	1.3
Metal, yielding pole or post	23	0.8
Metal, yielding barrier, guard rail	32	1.0
Metal, yielding blunt surface	21	0.7
Wood pole or post	44	1.4
Wood shrubbery	57	1.8
Other	100	3.2
Total	3100	100.0

THAILAND CASE DATA: MOTORCYCLIST INJURIES - A total of 4726 injuries were reported for all 1082 riders (helmeted and unhelmeted) and 1141 injuries for all 399 passengers (helmeted and unhelmeted), an average of 4.37 and 2.86 injuries per individual, respectively. For all reported injuries, 66% were AIS 1 (minor) injuries and approximately 9% of all injuries were AIS 4 or greater.

Injuries to the upper and lower extremities were most frequent. About 64% of injuries to both riders and passengers combined were to the extremities. Although injuries to the extremities were frequent, in the majority of cases they were not life threatening.

Motorcycle riders and passengers combined received 441 injuries to the head, which accounted for 7.5% of all injuries sustained. However, 52% of injuries to the head were AIS 4 or greater. A summary of injuries to all Thai motorcycle riders and passengers is found in Tables 4 and 5, respectively. In the 1082 investigated cases, slightly more than half of the riders were wearing a helmet and only about one-fifth of the passengers were wearing helmets at the time of the collision (Table 6), which is between the previously stated usage rates for urban (relatively high usage rate) and rural areas (relatively low usage rate).

Table 4 – AIS Injuries for all Thailand motorcycle riders (N=1082)

Region	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	AIS 6	AIS 9	Total
Head	79	62	20	76	114	6	0	357
Face	442	305	28	3	0	0	0	778
Neck	81	6	0	5	35	0	0	127
Thorax	104	4	20	38	74	17	0	257
Abdomen	79	3	27	7	29	6	0	151
Spine	8	0	0	0	56	8	0	72
Upper Ext.	1071	187	32	0	0	0	0	1290
Lower Ext.	1187	361	120	0	1	0	0	1669
Pelvis	4	8	7	0	6	0	0	25
Total	3055	936	254	129	315	37	0	4726

Table 5 – AIS Injuries for all Thailand motorcycle passengers (N=399)

Region	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	AIS 6	AIS 9	Total
Head	24	23	4	14	18	0	1	84
Face	90	60	6	0	0	0	0	156
Neck	16	0	0	1	4	0	0	21
Thorax	12	0	3	5	1	0	1	22
Abdomen	17	0	3	3	1	0	1	25
Spine	0	0	0	0	7	0	0	7
Upper Ext.	298	34	7	0	0	0	0	339
Lower Ext.	379	79	27	0	0	0	0	485
Pelvis	1	0	0	0	0	0	1	2
Total	837	196	50	23	31	0	4	1141

Table 6 - Helmet use by motorcycle rider and passenger

Helmet use	Motorcycle rider		Motorcycle passenger	
	Frequency	Percent	Frequency	Percent
No	528	48.8	323	81.0
Yes	554	51.2	76	19.0
Total	1082	100.0	399	100.0

A separate analysis was done for each of the 1082 motorcycle collisions on a case-by-case basis, relying on the investigation team's subjective evaluation of helmet effectiveness based on the accident reconstruction, kinematic analysis, and medical examination. This was performed because the relationship between helmet use and head injury varied among all collisions. For example, a rider might have no head injury because there was no impact to the helmet or the head. In another case, a rider might have serious head injury, yet examination of the helmet showed that it prevented far more severe (or even fatal) head injuries. In a different case, a helmet might be worn, but brain injuries might occur due to impact to the unprotected face, in which case the helmet would be judged to have had no effect on head injury. Other possibilities include situations in which a helmet flies off the rider's head, performs very poorly or is completely overwhelmed by impact loads. In these cases, the helmet performance might be judged as having "no effect" on head injury. The results of this analysis are shown in Table 7.

Table 7 – Helmet effectiveness evaluation

Helmet Effect	Frequency	Percent
No helmet, head injuries occurred	274	25.3
No contact, helmet worn or not worn	424	39.2
Helmet worn, but no effect on injuries	75	6.9
Helmet worn, reduced injuries	119	11.0
Helmet worn, prevented injuries	188	17.4
Unknown	2	0.2
Total	1082	100.0

REGRESSION ANALYSIS: HEAD MAIS - The best predictors of head MAIS were head impact geometry and Gadd Severity Index (GSI, Table 8). Head impact geometry (i.e. the geometry of the object struck) was the single best predictor of injury outcome (R^2 = .812). GSI was significant for entry into the second model (p. <.05) and increased the overall strength of the model (R^2 = .875). For the regression models, head impact geometry was coded as follows: flat=1, blunt=2, sharp edge=3, sharp object=4.

Table 8 – Stepwise regression model for MAIS

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.901	.812	.797	.864
2	.935	.875	.854	.733

1) Predictors: (Constant), Head Impact Geometry (coded)
2) Predictors: (Constant), Head Impact Geometry (coded), GSI

REGRESSION ANALYSIS: OVERALL ISS - Table 9 illustrates the best predictors for ISS, which were head impact geometry, liner thickness, and impact energy. Head impact geometry was entered into the first regression model (R^2 = .779). Liner thickness was added to the second model and increased the overall strength of the model (R^2 = .851). Finally, impact energy was added to the third model. The third model was relatvely strong with an R^2 value of .911.

Table 9 – Stepwise regression model for ISS

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.883	.779	.762	11.195
2	.922	.851	.826	9.577
3	.955	.911	.887	7.712

1) Predictors: (Constant), Head Impact Geometry (coded)
2) Predictors: (Constant), Head Impact Geometry (coded), Liner Thickness (mm)
3) Predictors: (Constant), Head Impact Geometry (coded), Liner Thickness (mm), Impact Energy (J)

DISCUSSION

There is limited research available regarding the best predictors of injury outcome in a motorcycle crash. Fortunately, on-scene in-depth crash investigations and laboratory helmet evaluation can yield a tremendous amount of information including physical evidence at the crash scene, crash reconstruction, medically diagnosed injuries, biomechanical data, helmet damage information, and head impact replication. The aim of this study was to collect variables present in a motorcycle crash environment, evaluate head impact severity and helmet effectiveness using a drop-test apparatus, and find the best predictors of injury outcome.

A limiting factor of this study is that in-depth data is not presented comparing cases where there was helmet damage but no head injury with cases where there was helmet damage with head injury. Knowing the magnitude of helmet damage and head impact force data, where the helmet eliminated head injury, is important in assessing the overall effectiveness of the helmets in preventing head injuries. However, a subjective helmet effectiveness evaluation was performed by the Thailand investigation team based on the accident reconstruction, kinematic analysis, helmet damage examination, and medical examination, which is depicted in Table 7. It was found that the helmet reduced or prevented head injury 28.4.% of the time. A more in-depth helmet damage replication study should include both helmet damage and head injury data, as well as a larger sample size. It is interesting to note that in 8 out of the 15 cases in this study, there was no injury to the head region (AIS score of 0), while all 15 helmets exhibited significant damage of varying magnitudes.

Another limitation of this study is that it involves only 15 helmets, which are specifically biased toward significant damage. Therefore, the predictive models may not be appropriate for all motorcycle crash circumstances. The physical characteristics of the 15 helmets were representative of the 220 collected (Table 1), except for the lack of polycarbonate helmet shells, and included a variety of crash circumstances. These 15 cases were not the only cases in which the helmet was damaged and the person was injured. However, helmets were excluded from this study, even if there was significant head injury, if the helmet had a poorly functioning retention system, if the motorcyclist did not use the retention system, if the helmet was either fully or partially ejected from the motorcyclist's head, if there was prior damage (a variable documented by the on-scene investigators), or if the helmet exhibited damage that could not be replicated due to the damage location or lack of an exemplar helmet.

The results of this study show that the overall best predictor of injury outcome was goemetry of the object struck by the head, as it was the first variable entered into both stepwise regression models. Impact geometry was coded according to the radii of the object struck (i.e., 1 = flat object, 2 = blunt object, 3 = sharp edge, and 4 = sharp penetrating object). The higher the geometry coding, the higher the injury score. This finding makes intuitive sense because it is well known that the risk of injury and the severity of injury are related to the geometry of the object applying the external load to the human body [Fung 1993].

GSI was also included in the MAIS regression model. It is important to note that peak head acceleration alone was not a good predictor of MAIS. Therefore, the results of this study suggest that duration of the linear head acceleration must also be considered when determining head injury potential. It should also be mentioned that the current study did not measure angular head acceleration during the replication studies. The decision to use a linear uni-axial accelerometer was made because one of the objectives of the study was to correlate helmet damage with the current Thailand motorcycle helmet standard [Thailand Department of Highways 1996]. Also, using a uni-axial twin wire apparatus created a more controlled laboratory environment. Recently, Newman et al. (2000) incorporated instrumented Hybrid III anthropomorphic test dummies (ATDs) into head impact drop testing to analyze both the linear and rotational effects of head injury. Future research using a similiar methodology with a different headform assembly may find that an injury criterion considering both linear and angular head acceleration values would be a better MAIS predictor than GSI.

It is interesting to note that HIC was found not to be a good predictor of injury outcome. Newman (1975) found similar results, in which HIC was not an accurate measure of brain/head injury potential for collision-involved helmeted motorcyclists.

For the ISS regression model, head impact geometery, liner thickness and impact energy were significant for entry. Although helmet liner thickness is directly related to force translated to the head (i.e. thicker helmets equate to greater energy absorption), in this study, it had implications for overall injury potential as well.

As expected, impact energy was positively correlated with ISS (i.e. as impact energy increased so did ISS score). For all fifteen cases analyzed, the replication test drop height was $\leq$ 1.75 meters. The geometry of the object struck was found to be a better predictor of injury outcome as opposed to impact energy, thus confirming that in the real world, serious injury can result from “aggressive” unyielding surfaces at relatively low impact energy levels. This finding contradicts some existing helmet standards that promote helmet protection systems that are designed to protect against high energy impacts and drop tested from extreme heights. While it is acknowledged that in some situations there is a need for helmets to absorb a high level of impact energy, the present study suggests that future motorcycle helmet manufacturing should focus upon shell and liner designs that will maximize energy absorption for a multitude of potential impact threats (i.e. relatively sharp or penetrating objects) rather than designing helmets to protect the head from increasing amounts of impact energy on relatively flat surfaces. This concept has also been proposed by other researchers [Thom and Hurt 1992].

The findings in this study also have implications for placement and geometry of “road furniture” (i.e., objects directly adjacent to the roadway). The predictive models clearly illustrate the influence that the geometry of the object struck has upon injury outcome. Frequently, sharp-edged posts and metal poles are located on the sidewalk, very close to the roadway. Furthermore, analysis of the data from the previous Thailand study showed that a significant number of motorcyclists came to rest on or near the sidewalk due to traffic collision avoidance maneuvers. These findings indicate the importance of accounting for the proximity and geometry of “road furniture” relative to the roadway by transportation design engineers to decrease injury potential for the collision involved motorcyclist. The observation was also made by Ouellet (1982).

Although they were not individually good predictors, helmet mass, shell thickness, and head impact surface (concrete, pavement, or metal) are indirectly related to impact energy and impact geometry, which were good predictors of injury outcome. Neither maximum liner crush nor liner crush area were found to be good injury predictors. However, they are both related to helmet liner thickness, because the more liner thickness and liner area available, the more material available for energy absorption.

The findings from this study illustrate the need for integrated injury causation analysis for motorcyclists involved in roadway collisions. The variables that were found to be good predictors of injury outcome involve data that has been derived from several different disciplines. Head impact geometry was recorded during the crash scene investigation, GSI and impact energy were calculated during helmet damage replication in the laboratory, liner thickness was measured in the laboratory, and medical information was generated by a trained medical professional. A truly accurate injury causation analysis should include cases where there was an impact to the helmet but no head injury and should rely upon expertise from as many different disciplines as possible (i.e., crash scene investigation, medical records, crash reconstruction, biomechanical analysis, helmet examination, and damage replication).

Future research will be conducted, using a larger sample size, using impact testing methodology of collision-involved Thai motorcycle helmets to evaluate the current Thailand motorcycle helmet standard and make recommendations for improvement.

CONCLUSIONS

The results of this study indicate that head impact geometry and GSI were the best predictors for Head MAIS. Head impact geometry, liner thickness, and impact energy were the best predictors for Overall ISS. The results of this study indicate that injury potential in motorcycle crashs is a multi-dimensional issue. The variables collected and analyzed in this study illustrate the need for multidisciplinary crash investigation including crash scene investigation, medical examination, crash reconstruction, biomechanical analysis, helmet examination, and damage replication.

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APPENDIX A

AIS coded injuries and crash speeds for the 15 cases

MAIS-ISS	Crash Speed (kph)	Head	Face	Neck	Thorax
0-3 (non-fatal)	55		210602.1		
			210202.1		
			210202.1		
			243099.1		
			251402.1		
0-3 (non-fatal)	60				
0-3 (non-fatal)	29		210202.1		
			210602.1		
0-3 (non-fatal)	33		210202.1		
			210202.1		
0-3 (non-fatal)	42		210602.1		
0-2 (non-fatal)	37		210402.1		
0-2 (non-fatal)	65				
0-3 (non-fatal)	27		210602.1		
			210202.1		
			210402.1		

MAIS-ISS	Crash Speed (kph)	Abdomen/ Pelvis	Spine	Upper Extremities	Lower Extremities
0-3 (non-fatal)	55			710202.1	810602.1
0-3 (non-fatal)	60	510202.1		751010.1	810202.1
				750800.1	810202.1
				710202.1	
				710202.1	
0-3 (non-fatal)	29			710202.1	810202.1
				710202.1	810202.1
					810202.1
0-3 (non-fatal)	33			710402.1	850802.1
				710202.1	
				710202.1	
0-3 (non-fatal)	42			710202.1	810202.1
0-2 (non-fatal)	37				810202.1
					810202.1
0-2 (non-fatal)	65			710202.1	810202.1
				710202.1	810202.1
0-3 (non-fatal)	27			710202.1	810202.1
				710202.1	810202.1

MAIS-ISS	Crash Speed (kph)	Head	Face	Neck	Thorax
4-50 (fatal)	55	110402.1	210202.1	310402.1	450804.2
		150406.4	210402.1	320220.3	441012.5
		140608.4		310402.1	441410.4
		140684.3		310402.1	
		110606.3		310402.1	
3-54 (fatal)	20	160810.3		320220.3	441406.3
		110402.1			
		110602.1			
4-29 (fatal)	27	150200.3		320499.2	450220.2
		150404.3		310402.1	410402.1
		110402.1			441406.3
		140688.4			
4-66 (fatal)	60	110402.1	210202.1	330299.2	410202.1
		110602.1	210202.1	310402.1	441006.4
		150402.2		310402.1	450240.4
		140688.4			441456.5
		140602.3			
		140602.3			
		140620.3			
4-41 (fatal)	55	110402.1	251800.2	310402.1	450804.2
		1504.02.2	250612.2	320208.3	441008.3
		150206.4	210202.1	310099.1	442202.3
		140688.4	210202.1	310099.1	420206.4
					441410.4
4-18 (fatal)	29	140688.4	210002.1		
		140684.3			
		150200.3			
1-38 (fatal)	62	110602.1	210602.1	310602.1	410202.1
					442610.5

MAIS-ISS	Crash Speed (kph)	Abdomen/ Pelvis	Spine	Upper Extremities	Lower Extremities
4-50 (fatal)	55		650216.2	752604.3	810202.1
			650216.2		810202.1
			650230.2		
			650216.2		
3-54 (fatal)	20	543800.3	640278.1		
		543800.3	640278.1		
			640278.1		
			640232.6		
4-29 (fatal)	27	541822.2	650208.2	752200.2	810202.1
				752200.2	810202.1
				710202.1	
4-66 (fatal)	60	541822.2	650230.2	710202.1	853000.3
		544228.5		710202.1	810202.1
		541628.5		752604.3	810202.1
		541628.5			810202.1
		542810.2			851814.3
					853422.3
					851606.2
4-41 (fatal)	55	544222.2	650208.2	752604.3	851814.3
		541822.2	650230.2	710202.1	853422.3
			650430.2	710202.1	810202.1
					810202.1
					810202.1
					810602.1
4-18 (fatal)	29				810202.1
1-38 (fatal)	62		650208.2	710202.1	851606.2
			640278.1	710202.1	853422.3