Accident Analysis and Prevention 91 (2016) 200–207

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Motorcycle helmet use and the risk of head, neck, and fatal injury: Revisiting the Hurt Study

Thomas M. Rice[a,*], Lara Troszak[a], James V. Ouellet[a,b], Taryn Erhardt[a], Gordon S. Smith[a,c], Bor-Wen Tsai[a]

[a] University of California Berkeley, United States
[b] Motorcycle Accident Analysis, Playa del Rey, CA, United States
[c] University of Maryland School of Medicine, United States

ARTICLE INFO

Article history:
Received 16 November 2015
Received in revised form 11 February 2016
Accepted 3 March 2016

Keywords:
Motorcycle
Helmet
Head injury
Neck injury
Fatality
California

ABSTRACT

Most studies find strong evidence that motorcycle helmets protect against injury, but a small number of controversial studies have reported a positive association between helmet use and neck injury. The most commonly cited paper is that of Goldstein (1986). Goldstein obtained and reanalyzed data from the Hurt Study, a prospective, on-scene investigation of 900 motorcycle collisions in the city of Los Angeles. The Goldstein results have been adopted by the anti-helmet community to justify resistance to compulsory motorcycle helmet use on the grounds that helmets may cause neck injuries due to their mass. In the current study, we replicated Goldstein's models to understand how he obtained his unexpected results, and we then applied modern statistical methods to estimate the association of motorcycle helmet use with head injury, fatal injury, and neck injury among collision-involved motorcyclists. We found Goldstein's analysis to be critically flawed due to improper data imputation, modeling of extremely sparse data, and misinterpretation of model coefficients. Our new analysis showed that motorcycle helmets were associated with markedly lower risk of head injury (RR 0.40, 95% CI 0.31–0.52) and fatal injury (RR 0.44, 95% CI 0.26–0.74) and with moderately lower but statistically significant risk of neck injury (RR 0.63, 95% CI 0.40–0.99), after controlling for multiple potential confounders.

1. Introduction

Most studies find strong evidence that motorcycle helmets protect against injuries during traffic collisions but some studies have claimed a positive association between helmet use and neck injury. Numerous studies have looked at the possible role of motorcycle helmets in the causation of neck injury among motorcyclists during traffic collisions. Liu et al. (2004) conducted a Cochrane review of the effects of motorcycle helmet on fatality, head injury, and neck injury. They identified 16 studies that used neck injury as an outcome and reported that the data could not support any conclusion about the possible association between helmet use and the occurrence of neck injury. They estimated a pooled odds ratio of 0.85 (95% CI 0.66–1.09, p 0.69) for neck injuries.

A small number of studies have reported a positive association between motorcycle helmet use and neck injury. The most commonly cited paper is that of Goldstein (1986). Goldstein obtained the final data sets from the Hurt Study, a prospective, on-scene, in-depth investigation and reconstruction of 900 motorcycle collisions in the city of Los Angeles (Hurt et al., 1981a). Hurt's team of motorcyclist-investigators conducted their independent crash scene evidence collection during police investigation immediately after a collision (627 cases) or within 24 h (283 cases). They interviewed riders and other motorists, photographed vehicles and skids, and obtained 261 of 355 helmets riders wore when they crashed. They later compiled this evidence to identify crash and injury causation.

Goldstein applied probit and Tobit models to the Hurt Study data and drew three primary conclusions: (1) helmets provided protection against head injury, (2) helmets had no influence on fatal injury, and (3) helmets caused neck injuries at impact speeds of 13 MPH or greater. Several authors have criticized Goldstein's methods (Bedi, 1987; Weiss, 1992; Lawrence et al., 2003) and his results are incompatible with a majority of the published research. Hurt Study researchers have questioned the findings because Goldstein's analysis used an independent variable called "normal component of impact velocity" to the helmet that they

* Corresponding author at: Safe Transportation Research & Education Center, 2614 Dwight Way #7374, Berkeley, CA 94720-7374, United States.
E-mail address: tomrice@berkeley.edu (T.M. Rice).

http://dx.doi.org/10.1016/j.aap.2016.03.002
0001-4575/

recorded for 5% of helmeted motorcycle riders. The Hurt Study investigators found that it was usually impossible to accurately estimate the normal component of impact velocity value and discontinued its collection early in the study, thus the value was missing for a large majority of helmeted riders. Because this variable appeared in the Helmet section of the Hurt Study data forms, it was recorded as “not applicable” for all of the unhelmeted riders. This variable is almost always much less than the motorcycle crash speed. For example, during a crash, if the helmet hits the horizontal pavement at a vertical, downward speed of 9½ mph (the equivalent of an uninterrupted 3-foot drop), then 9½ mph is the normal component of impact velocity to the helmet, whether the motorcycle rider was traveling horizontally, parallel to the pavement at 1, 10 or 100 MPH just before the crash.

Because Goldstein’s unexpected results are so widely known (among motorcyclists and, particularly, among individuals and groups involved in anti-helmet activities), we aimed to (1) obtain and analyze the same data from the Hurt Study that Goldstein used, (2) replicate the analysis performed by Goldstein, and (3) reanalyze the data using modern statistical models not available at the time of Goldstein’s analysis.

2. Methods and procedures

The Hurt Study involved the detailed, on-scene investigation of motorcycle collisions in Los Angeles, California that occurred between January 1976 and December 1977 (Hurt et al., 1981a). Hurt’s investigators collected data through direct observation, photography and measurement of physical evidence, medical documents, personal interviews with motorcyclists, other vehicle drivers and victims, and witnesses. Data were also collected at hospital emergency departments, coroner offices, and at tow yards. They collected 261 of 355 helmets worn and kept them for examination and disassembly to identify and record all damage. In order to encode head-neck injuries in much greater detail than existing coding systems allowed, the Hurt Study investigators created a head-neck injury coding system modeled on the Occupant Injury Classification (OIC) (Marsh, 1973). The OIC was an alphabetic injury coding system that predated and set the pattern for the all-numeric Abbreviated Injury Scale (AIS). As with the current AIS, the system encoded each injury by location (body region, side, and aspect), system or organ involved, and type of injury (abrasion, fracture, laceration, etc). Injury severity was coded by consulting resident pathologists using the 1976 version of the AIS (American Association for Automotive Medicine, 1976). Ouellet et al. (1984) published a detailed description of the head-neck injury coding system used in the Hurt Study. Each Hurt Study case involved answering roughly 400–500 questions about the crash. Many were simple questions such as the day of the week, motorcycle manufacturer, or rider gender. Others were much more complex, such as vehicle speeds, crash causes, and contributing factors. When all data had been collected, each case was reconstructed to determine elements such as crash speed, collision avoidance actions, accident cause, and injury-causing contacts.

Hurt Study data sets, data outputs, and documentation were obtained directly from the Hurt Study investigators. The final data sets from the study were obtained in SPSS format or as ASCII files. We had the advantage of using the Hurt Study data forms (Hurt et al., 1981b) and guidance from Hurt study authors (David R. Thom, James V. Ouellet, and Terry Smith) to assure that data within the original flat files were properly organized and understood. Data were converted to Stata format, and separate files were created for 900 motorcyclists, 861 head, neck, or facial injuries, and 3020 below-the-neck injuries.

2.1. Replication of Goldstein analysis

To identify the subset of 644 riders used by Goldstein, we obtained a data output provided by Goldstein to the Hurt Study investigators after the completion of his analysis. Goldstein’s 1986 publication provided details on how variables were prepared and we attempted to duplicate all of his data procedures. We recreated the head injury severity measure, as Goldstein did, using the sum of the squared AIS scores for all head injuries; we also recreated the neck injury severity measure using the sum of the squared AIS scores for all neck injuries. Consistent with Goldstein, we fitted a probit model using a fatality indicator as the outcome, and we fitted a Tobit model using each of the head and neck injury severity measures as the outcome. The probit and Tobit models were fitted using Stata’s ‘probit’ and ‘tobit’ procedures, respectively. Goldstein used two methods for calculation of kinetic energy. We used his first method in our replication models because Goldstein indicated that the first method improved the fit of his models to the data. Goldstein also included single year of age, blood alcohol concentration, evasive action taken by rider (yes/no), street motorcycling experience (months), and helmet by rider weight interaction. We included these variables in our replication models.

2.2. New analysis

The objective of our new analysis was to estimate the associations between helmet use and the occurrence of three outcomes among the 900 collision-involved motorcyclists in the Hurt Study database. The outcomes were neck injury, head injury, and fatal injury. We developed directed acyclic causal graphs to identify potential confounders of the helmet-injury associations (Greenland et al., 1999). We identified rider age, rider sex, rider alcohol use, motorcycle type, motorcycle collision speed, collision type, number of involved vehicles, type of object struck, rider evasive action pre-collision, distance between rider point of rest and collision point of impact, and below-the-neck injury severity as potential confounders. We defined neck injuries as injuries coded as ‘cervical vertebra 1–7 plus adjacent superior joints,’ ‘cervical-general,’ or ‘throat.’ The most severe injury in each of the head, neck, and below-the-neck regions was calculated for each rider. Due to the small number of AIS >1 neck injuries ($n = 16$), we used the presence of a neck injury of any severity (AIS >0) as the outcome.

Bivariate associations were examined using Pearson Chi-sq or Fischer’s exact tests. We estimated crude risk ratios (RR) and adjusted risk ratios (aRR) using log-binomial regression (Barros and Hirakata, 2003; McNutt et al., 2003; Vittinghoff et al., 2012). Potential confounders were included in the model if they were significant predictors of neck injury at $p < 0.15$ or if their removal from the model resulted in a change of 10% or greater in the helmet use coefficient. Age was modeled as continuous, quadratic, and categorical. The other model coefficients were nearly identical across the three approaches, and age categories were used for the result tables. Motorcycle speed was also modeled as continuous, quadratic, and continuous. The models with continuous motorcycle speed were as informative as the others, so these models were used. All models were fitted to data on 882 riders (98%) for whom age, sex, motorcycle speed, and helmet use status were known. All data management and analysis was done with Stata 13 (StataCorp, 2014).

3. Results

The Hurt Study collected data on 900 motorcycle operators involved in traffic collisions (Table 1). Forty percent of riders were helmeted at the time of collision. The sample is dominated by young male riders; 85% were aged 34 or younger, and 96% were male.

Table 1
Motorcyclist, collision, and motorcycle characteristics by helmet use, Hurt Study, Los Angeles, 1976–1977.

Characteristic	Helmet use						p[b]
	No		Yes		Total[a]		
	No.	%	No.	%	No.	%	
Motorcyclist age							<0.001
21 or younger	213	39.7%	105	29.6%	318	35.7%	
22–25	136	25.3%	73	20.6%	209	23.4%	
26–34	130	24.2%	100	28.2%	230	25.8%	
35–49	41	7.6%	53	14.9%	94	10.5%	
50 or older	11	2.0%	22	6.2%	33	3.7%	
Unknown	6	1.1%	2	0.6%	8	0.9%	
Motorcyclist sex							0.600
Female	19	3.5%	15	4.2%	34	3.8%	
Male	518	96.5%	340	95.8%	858	96.2%	
Street motorcycling experience							0.189
0–6 mos	21	3.9%	8	2.3%	29	3.3%	
7–12 mos	71	13.2%	39	11.0%	110	12.3%	
1–2 yrs	73	13.6%	52	14.6%	125	14.0%	
2–3 yrs	57	10.6%	49	13.8%	106	11.9%	
3–4 yrs	41	7.6%	30	8.5%	71	8.0%	
4 yrs or more	182	33.9%	157	44.2%	339	38.0%	
Unknown	92	17.1%	20	5.6%	112	12.6%	
Type of motorcycle							<0.001
Street OEM	337	62.8%	281	79.2%	618	69.3%	
Dirt	12	2.2%	2	0.6%	14	1.6%	
Enduro	64	11.9%	34	9.6%	98	11.0%	
Semi-chopper	48	8.9%	15	4.2%	63	7.1%	
Chopper	46	8.6%	3	0.8%	49	5.5%	
Cafe racer	13	2.4%	15	4.2%	28	3.1%	
Other	17	3.2%	5	1.4%	22	2.5%	
Motorcycle make							<0.001
BMW	6	1.1%	8	2.3%	14	1.6%	
Harley-Davidson	71	13.2%	23	6.5%	94	10.5%	
Honda	299	55.7%	198	55.8%	497	55.7%	
Kawasaki	30	5.6%	43	12.1%	73	8.2%	
Suzuki	21	3.9%	19	5.4%	40	4.5%	
Triumph	14	2.6%	4	1.1%	18	2.0%	
Yamaha	63	11.7%	46	13.0%	109	12.2%	
Unknown	33	6.1%	14	3.9%	47	5.3%	
Speed limit							<0.001
15–25 MPH	167	31.1	76	21.4	243	27.2	
30–35 MPH	301	56.1	209	58.9	510	57.2	
40–45 MPH	20	3.7	24	6.8	44	4.9	
50–55 MPH	35	6.5	41	11.5	76	8.5	
Unknown	14	2.6	5	1.4	19	2.1	
MC speed category							0.275
Stopped	6	1.1	11	3.1	17	1.9	
1–19 MPH	197	36.7	120	33.8	317	35.5	
20–29 MPH	188	35.0	116	32.7	304	34.1	
30–39 MPH	92	17.1	68	19.2	160	17.9	
40–49	28	5.2	23	6.5	51	5.7	
50–75 MPH	25	4.7	16	4.5	41	4.6	
Unknown	1	0.2	1	0.3	2	0.2	
Intersection collision							0.030
No	162	30.2	132	37.2	294	33.0	
Yes	372	69.3	222	62.5	594	66.6	
Unknown	3	0.6	1	0.3	4	0.4	
MC motion pre-impact							0.022
Going straight	388	72.3	239	67.3	627	70.3	
Overtaking	24	4.5	18	5.1	42	4.7	
Turning	42	7.8	26	7.3	68	7.6	
Unsafe turn or U-turn	30	5.6	15	4.2	45	5.0	
Stopping or stopped	10	1.9	16	4.5	26	2.9	
Entering traffic	14	2.6	5	1.4	19	2.1	
Changing lanes	13	2.4	16	4.5	29	3.3	
Other	14	2.6	20	5.6	34	3.8	
Unknown	2	0.4	0	0.0	2	0.2	
Rider motion post impact							0.954
Stopped near POI	50	9.3	32	9.0	82	9.2	
Vaulted from MC	146	27.2	92	25.9	238	26.7	
Fell from MC	134	25.0	96	27.0	230	25.8	
Tumbled/rolled/slid to stop	134	25.0	84	23.7	218	24.4	

Motorcyclist, collision, and motorcycle characteristics by helmet use, Hurt Study, Los Angeles, 1976–1977.

Characteristic	Helmet use						p[b]
	No		Yes		Total[a]		
	No.	%	No.	%	No.	%	
Struck/trapped/dragged by veh.	66	12.3	45	12.7	111	12.4	
Unknown	7	1.3	6	1.7	13	1.5	
Rider point of rest (ft)							0.869
0–12 ft	163	30.4	114	32.1	277	31.1	
13–25 ft	128	23.8	75	21.1	203	22.8	
26–50 ft	108	20.1	78	22.0	186	20.9	
51–100 ft	57	10.6	38	10.7	95	10.7	
100 ft or more	27	5.0	19	5.4	46	5.2	
Unknown	54	10.1	31	8.7	85	9.5	
Fatal injury							0.009
No	496	92.4	343	96.6	839	94.1	
Yes	41	7.6	12	3.4	53	5.9	
Total[a]	537	100	355	100	892	100	

[a] Excludes 8 motorcycle riders with unknown helmet status.
[b] *p*-value from Pearson chi-squared test or Fisher's exact test.

These riders had little riding experience. Of the 780 with known information on riding experience, 57% had less than 4 years of experience. The most common motorcycle brands were Honda (56%), Yamaha (12%), and Harley-Davidson (11%). The collisions were relatively low-speed collisions with a median of about 22 mph. Of all riders, 87% were traveling 39 MPH or less at the point of collision and 84% were on roadways with speed limits of 35 MPH or less. Two-thirds of collisions occurred at intersections, usually when a car violated the motorcycle right-of-way.

The 900 motorcyclists suffered a total of 102 neck injuries, 423 head injuries, 328 facial injuries, and 3020 below-the-neck injuries (Table 2). A large majority of all injuries were minor (AIS 1) or moderate (AIS 2) severity, but the severity distribution varied across body regions. Facial injuries were notably less severe than those in other body regions; 83% of facial injuries were AIS 1 (minor) and the remainder were AIS 2 (13%) or AIS 3 (2.7%). Neck injuries were the least common injury, 102 out of 3873 total injuries (2.6%). Three-quarters of neck injuries were AIS 1 (minor) and a small number of neck injuries were AIS 5 or 6 (10.8%). Injuries to the head region numbered 423 with only 51% being AIS 1 (minor). A total of 87 head injuries were AIS 4 (severe) or greater (21%). Below-the-neck injuries were the most prevalent and accounted for 78% of all injuries. Of all 250 injuries with a severity of AIS 3 or greater, 60% were below-the-neck injuries, 35% were head injuries, and 4.8% were neck injuries.

The 102 neck injuries were suffered by 88 motorcycle riders. Seventy-two of the 88 riders (82%) suffered an AIS 1 injury as their most severe neck injury (Table 3). Nine of them (10%) suffered an AIS 5 (critical) or AIS 6 (unsurvivable) neck injury; 8 of the 9 were fatalities with very high below-the-neck or head injuries. Of the 88 riders, 48 also suffered one or more head injuries. Twenty-three had only AIS 1 injury and 25 had a more severe head injury. Thirty-five riders suffered a facial injury, all of which were AIS $\leq$3 (minor to serious). All 88 riders also suffered at least one below-the-neck injury. For 65 of the 88 riders (75%) the most severe below-the-neck injury was AIS 1 or 2.

Table 4 shows the neck injury severity score calculated using the method Goldstein described for the 644 motorcyclists in his analysis (277 helmeted and 367 unhelmeted). Goldstein's approach was to take the AIS scores for all neck injuries, square them, and sum them for each rider. Among Goldstein's helmeted riders, only one rider suffered a neck injury more severe than AIS 1 (minor). The rider had three separate neck injuries with AIS values of 1, 3, and 6. This rider was assigned a neck injury severity score of $1^2+3^2+6^2=46$. (This fatally injured rider also suffered 4 head injuries and 8 below-the-neck injuries, consistent with a very severe collision.) The other 19 helmeted riders with neck injury had only a single injury of AIS 1 and were thus given a severity score of 1. Among his unhelmeted riders, 8 riders had a neck injury severity score greater than 1, and the remaining 34 neck injured riders had a severity score of 1. Several unhelmeted riders had very high scores, reflecting multiple neck injuries. For example, the rider with a neck injury severity score of 66 had 4 neck injuries of AIS scores 1 (minor), 2 (moderate), 5 (critical), and 6 (unsurvivable).

In Table 5, we present the helmet use coefficients, standard errors (SE), and *p*-values reported by Goldstein and those obtained

Table 2
Injuries by body region and AIS[a] severity among 900 motorcycle riders, Hurt Study, Los Angeles, 1976–1977.

Body region and AIS severity	No.	%
Neck (N = 102)		
AIS 1 (Minor)	76	74.5%
AIS 2 (Moderate)	4	3.9%
AIS 3 (Serious)	10	9.8%
AIS 4 (Severe)	1	1.0%
AIS 5 (Critical)	4	3.9%
AIS 6 (Unsurvivable)	7	6.9%
Head (N = 423)		
AIS 1	217	51.3
AIS 2	64	15.1
AIS 3	55	13.0
AIS 4	27	6.4
AIS 5	44	10.4
AIS 6	16	3.8
Face (N = 328)		
AIS 1	275	83.8
AIS 2	44	13.4
AIS 3	9	2.7
AIS 4	0	0
AIS 5	0	0
AIS 6	0	0
Somatic[b] (N = 3020)		
AIS 1	2269	75.1
AIS 2	384	12.7
AIS 3	216	7.2
AIS 4	99	3.3
AIS 5	40	1.3
AIS 6	12	0.4
Total[c]	3873	100

[a] Abbreviated Injury Scale, 1976 revision.
[b] Injuries below the neck.
[c] Excludes 9 injuries with unknown body region.

Table 3
Most severe injury by body region, 88 motorcycle riders with neck injury, Hurt Study, Los Angeles, 1976–1977.

Most severe injury	No.	%
Neck		
AIS 1 (Minor)[a]	72	81.8
AIS 2 (Moderate)	1	1.1
AIS 3 (Serious)	6	6.8
AIS 4 (Severe)	0	0
AIS 5 (Critical)	2	2.3
AIS 6 (Unsurvivable)	7	8.0
Head[b]		
None	40	45.5
AIS 1	23	26.1
AIS 2	6	6.8
AIS 3	7	8.0
AIS 4	3	3.4
AIS 5	3	3.4
AIS 6	6	6.8
Face		
None	53	60.2
AIS 1	22	25.0
AIS 2	9	10.2
AIS 3	4	4.5
AIS 4	0	0
AIS 5	0	0
AIS 6	0	0
Somatic[c]		
None	0	0
AIS 1	46	53.3
AIS 2	19	21.6
AIS 3	11	12.5
AIS 4	4	4.5
AIS 5	5	5.7
AIS 6	3	3.4
Total	88	100

[a] Abbreviated Injury Scale, 1976 revision.
[b] Excludes face.
[c] Injuries below the neck.

Table 4
Neck injury severity measure by helmet use among motorcyclists, Goldstein data set (n = 644), Hurt Study, Los Angeles, 1976–1977.

Neck injury SS[a]	Helmet use					
	No		Yes		Total	
	No.	%	No.	%	No.	%
0	325	88.6	257	92.8	582	90.4
1	34	9.3	19	6.9	53	8.2
9	3	0.8	0	0	3	0.5
25	1	0.3	0	0	1	0.2
36	1	0.3	0	0	1	0.2
45	1	0.3	0	0	1	0.2
46	0	0	1	0.4	1	0.2
66	1	0.3	0	0	1	0.2
71	1	0.3	0	0	1	0.2
Total	367	100	277	100	644	100

[a] Severity score as calculated by Goldstein: sum of squared AIS severity scores for all neck injuries.

in our replication of his analysis. When we included the normal component interaction term (with "imputed" missing values per Goldstein) in the replication models, our coefficients and SE's were nearly identical to those of Goldstein. When we removed the normal component interaction term from our model, the coefficients were substantially different for the fatal injury model (−0.60 vs −1.20) and for the head injury model (−13.34 vs −17.18). The difference was much greater in the neck injury model (−6.39 vs −21.38).

Table 6 presents our selected model to estimate neck injury risk ratios using a modern statistical approach. The outcome measure in this model was the occurrence of one or more neck injuries. The adjusted neck injury risk ratio (aRR) for helmet use was 0.63 (95% confidence interval [CI] 0.40–0.99), indicating a protective effect, and was significant at $p = 0.044$. Age was a weakly associated with neck injury occurrence (p 0.119), with estimated risk ratios for riders in the 26–34 year old category or older elevated compared with riders aged 25 years or younger. Age was a modest confounder of the helmet-neck injury association in each of our three approaches to modeling age (linear, quadratic, and categorical). Removing age from the model resulted in a 16–18% decrease (away from the null) in the helmet coefficient. Neither sex (p 0.267) nor alcohol/drug use (p 0.551) was a significant predictor of neck injury. The aRR for each 10 MPH increase in motorcycle speed was 1.12 (0.97–1.30, p 0.112). Most severe below-the-neck injury was a significant predictor of neck injury at $p = 0.060$. AIS 5 (critical) or AIS 6 (unsurvivable) injuries below the neck signify extremely severe collision conditions and those riders in such extreme crashes appeared to be more

Table 5
Estimated helmet use coefficient, standard error, and 95% confidence intervals, Goldstein and replicated analyses, Hurt Study, Los Angeles, 1976–1977.

			Normal component of helmet impact velocity term used in model[a]	
			Yes	No
Outcome	Model	Goldstein beta[b] (SE) p	Replicated beta[c] (SE) p	Replicated beta (SE) p
Fatal injury indicator	Probit	−1.22 (0.84) 0.07	−1.20 (0.83) 0.15	−0.60 (0.23) 0.01
Head injury SS[d]	Tobit	−17.24 (4.82) <0.001	−17.18 (4.73) <0.001	−13.34 (2.20) <0.001
Neck injury SS[e]	Tobit	−21.34 (8.27) 0.01	−21.38 (8.99) 0.02	−6.39 (2.53) 0.01

[a] Normal component of helmet impact velocity by helmet use product term.
[b] Model coefficient reported by Goldstein (1986).
[c] Replicated model using 644 motorcyclists used in Goldstein analysis.
[d] Severity score calculated as the sum of the squared AIS severity scores for all head injuries.
[e] Severity score calculated as the sum of the squared AIS severity scores for all neck injuries.

Table 6
Re-analysis of data showing unadjusted and adjusted neck injury risk ratios, 95% confidence intervals, and *p*-values among collision-involved motorcyclists, Hurt Study, Los Angeles, 1976–1977.

Characteristic	Riders[a]	Neck injury (%)	RR[b]	95% CI[c]	p	aRR[d]	95% CI	p
Helmet use					0.066			0.045
No	530	61 (11.5)	ref.	–		ref.	–	
Yes	352	27 (7.7)	0.67	0.43–1.03		0.63	0.40–0.99	
Age					0.113			0.119
21 or younger	317	25 (7.9)	ref.	–		ref.	–	
22–25	209	17 (8.1)	1.03	0.57–1.86		1.01	0.56–1.81	
26–34	229	33 (14.4)	1.83	1.12–2.99		1.81	1.11–2.95	
35–49	94	9 (9.6)	1.21	0.59–2.51		1.27	0.62–2.64	
50 or older	33	4 (12.1)	1.54	0.57–4.15		1.65	0.63–4.35	
Sex					0.339			0.262
Female	34	5 (14.7)	ref.	–		ref.	–	
Male	848	83 (9.8)	0.67	0.29–1.53		0.62	0.27–1.44	
Alcohol or drug use					0.298			0.537
No	781	75 (9.6)	ref.	–		ref.	–	
Yes	101	13 (12.9)	1.34	0.77–2.33		0.83	0.46–1.49	
Most severe below-the-neck injury					0.060			0.318
None	30	3 (10.0)	1.12	0.37–3.41		1.13	0.37–3.45	
AIS 1 (Minor)	483	43 (8.9)	ref.	–		ref.	–	
AIS 2 (Moderate)	181	19 (10.5)	1.18	0.71–1.97		1.16	0.70–1.93	
AIS 3 (Serious)	105	11 (10.5)	1.18	0.63–2.21		1.16	0.62–2.17	
AIS 4 (Severe)	54	4 (7.4)	0.83	0.31–2.23		0.82	0.31–2.15	
AIS 5 (Critical)	18	5 (27.8)	3.12	1.40–6.93		2.71	1.19–6.18	
AIS 6 (Maximal)	11	3 (27.3)	3.06	1.12–8.38		2.07	0.77–5.54	
Motorcycle speed[e]	–	–	1.17	1.00–1.37	0.041	1.12	0.97–1.30	0.121

[a] Total riders = 882 (18 motorcycle riders with unknown values for helmet use, age, sex, or motorcycle speed excluded).
[b] Unadjusted risk ratio.
[c] Confidence interval.
[d] Adjusted risk ratio.
[e] Risk ratio per 10 MPH increase.

Table 7
Re-analysis of data showing unadjusted and adjusted head injury risk ratios and fatal injury risk ratios for helmet use, 95% confidence intervals, and *p*-values among collision-involved motorcyclists, Hurt Study, Los Angeles, 1976–1977.

Outcome	Helmet use	Riders[a]	Number injured (%)	RR[b]	95% CIc[c]	p	aRR[d]	95% CI	p
Head injury	No	530	207 (39.1)	ref.	–		ref.	–	
	Yes	352	55 (15.6)	0.40	0.31–0.52	<0.001	0.40	0.31–0.52	<0.001
Fatal injury	No	530	40 (7.6)	ref.	–		ref.	–	
	Yes	352	12 (3.4)	0.45	0.24–0.85	0.014	0.44	0.26–0.74	0.002

[a] Total riders = 882 (18 motorcycle riders with unknown values for helmet use, age, sex, or motorcycle speed excluded).
[b] Unadjusted risk ratio.
[c] Confidence interval.
[d] Risk ratio adjusted for age, sex, alcohol use, motorcycle speed, and most severe below-the-neck injury.

likely to suffer neck injury. No rider with AIS 5 or AIS 6 below-the-neck injuries survived.

Table 7 shows the head injury helmet risk ratios and fatal injury risk ratios estimated using models with the same set of covariates used in the neck injury model. The adjusted head injury risk ratio for helmet use was 0.40 (95% CI 0.31–0.52). The adjusted fatal injury risk ratio for helmet use was 0.44 (95% CI 0.26–0.74).

4. Discussion

In his 1986 journal article published in the social science journal Evaluation Review Goldstein reported the results of his re-analysis of data from the 1981 Hurt Study, a landmark study of motorcycle collisions. Goldstein examined how helmet use affected three outcomes, fatal injury, head injury, and neck injury. Here, we have replicated his regression models and have conducted new analyses of the original Hurt Study data set using a well-established approach to modeling binary outcomes. We find that Goldstein's models were egregiously deficient and his findings incorrect for several reasons: (1) he improperly imputed values for a variable that almost always had missing values; (2) he calculated overall head injury severity and overall neck injury severity using an unknown and untested method; (3) his neck injury severity models were based on extremely sparse data; (4) he biased his helmet use coefficients by including a second model term closely related to helmet use (using the "imputed" values); and (5) he misinterpreted his model coefficients to draw unsupported conclusions. More detailed explanations follow.

Goldstein claimed that the normal component of impact velocity was a critically important variable to include in an analysis of helmet effectiveness. The Hurt Study investigators attempted to estimate this value for helmeted riders early on in their study. After determining the value for 22 helmeted riders, they discontinued the collection of this variable. The remaining 333 helmeted riders, all 537 unhelmeted riders, and 8 riders with unknown helmet status had a missing "normal component" value at the end of the study.

Goldstein's sample consisted of 277 helmeted riders and 367 unhelmeted riders. Of the 277 helmeted riders, only 15 riders (5.4%) had a known value for this variable. Goldstein assigned the mean value (10.13) to the remaining 262 helmeted riders (94.6%). And by including only the product term of helmet use (1 = helmet worn, 0 = no helmet) and normal component in the model, he effectively assigned 0 to all 367 unhelmeted riders. Thus, Goldstein invented normal component values for 97.7% of the riders in his data set.

The assignment of values to this unknown factor is extremely problematic. Goldstein referred to it as data imputation. We view it as data fabrication since the vast majority of assignments are certain to have been wrong. His assignment was based on only 15 actual normal component values. His assignment of 0 to all unhelmeted riders is certainly wrong for any unhelmeted rider who took an impact to the head region, and his assignment of 10.13 to any helmeted rider who did not take an impact to the head (a large majority of riders) was also wrong. The use of such single-value imputation methods is widely known to be problematic. Little (1992) warned that "... inferences (tests and confidence intervals) are seriously distorted by bias and overstated precision," and "Unconditional mean imputation cannot be generally recommended." Pigott (2001) noted that "Bias in the estimation of variances and standard errors are compounded when estimating multivariate parameters such as regression coefficients. Under no circumstances does mean imputation produce unbiased results."

Goldstein also incorrectly calculated neck injury severity by summing the squares of all neck injuries for each rider. He appears to have adapted the method for calculating the Injury Severity Score (ISS) (Baker et al., 1974). The ISS is a measure of overall injury severity to the entire body in which the highest AIS severity score in each of the three most severely injured body regions are squared and then summed. Because the ISS ignores the possible effect of multiple injuries in one region, other methods, like the New Injury Severity Score (Osler et al., 1997) use the three most severe injuries regardless of body region. No known method summarizes the severities of all injuries within one region.

Goldstein's neck injury model was driven by a small number of riders with neck injury more severe than AIS 1 (minor). Table 4 shows the inadequacy of his sample for modeling neck injury severity. Only 8 unhelmeted riders and one helmeted rider had a neck injury more severe than AIS 1 (minor) neck injury. These data simply cannot support a reliable analysis of the association between helmet use and neck injury severity, regardless of statistical method, as Hurt et al. properly noted in their original report (pp 300–302).

The 9 riders with neck injury more severe than AIS 1 that Goldstein relied on were involved in severe collisions and each suffered multiple injuries (between 7 and 16) in multiple body regions. Eight of the 9 riders died from their injuries. These riders and their collisions represented a small minority of Hurt Study motorcyclists involved in severe collisions and their more severe neck injuries were not particularly important to their overall disposition, given the preponderance of severe head and thorax injuries.

Goldstein included his fabricated normal component interaction term in his models. Because this term is similar to the helmet use indicator (it is 0 for unhelmeted riders and some positive value for helmeted riders) it served to model out some of the helmet effect, altering the value of the estimated coefficient of the helmet use indicator. Our replication showed that the inclusion of this unusual term altered his helmet use coefficient by approximately a two-fold in his fatality model and caused him to incorrectly claim that helmet use was not associated with reductions in fatality. Removal of the term would have given him a significant reduction of fatality risk (p 0.01). The inclusion of the term altered the helmet use coefficient in his head injury model by 29%. Most importantly, its inclusion in his neck injury severity model altered his helmet use coefficient from −6.39 to −21.38, a 235% increase.

The inclusion of this normal component interaction term in the model is especially troubling because his overall findings are so dependent on this variable. Perhaps Goldstein's idea was to include the helmet indicator, the normal component of impact velocity variable, and the interaction between the two to be able to examine how the helmet coefficients varied across levels of normal component. But he did not do that. He did not include the main term for normal component; he included only the helmet term and the interaction term.

Goldstein then went on to improperly interpret his neck injury severity model. Even if one assumes his model to be correct, any reasonable interpretation of his regression output would have been that, after accounting for head impact velocity, helmet use greatly reduced neck injury severity (beta −21.34, p 0.01). Instead, he calculated the impact velocity (13 MPH) that would change the predicted neck injury severity by an amount equal to that of the helmet use coefficient. He concluded from this calculation that "...past a critical impact velocity to the helmet, as measured by the normal component of velocity, helmet use has a statistically significant effect that exacerbates the severity of neck injuries." Nowhere in his reported regression results is this interpretation supported; his helmet use coefficient was negative and its *p*-value was small. Moreover, of the 15 motorcycle riders with a known normal component of impact velocity value in Goldstein's data set, only 4 had a normal component value of 13 MPH or greater. These 4 riders were helmeted and completely free of neck injury.

In our new analyses of the Hurt Study data, helmeted riders were estimated to be 37% less likely to suffer neck injury than unhelmeted riders (p 0.044), after accounting for differences in rider age, sex, alcohol use, motorcycle speed, and most severe below-the-neck injury. Motorcycle helmets were also associated with a large reduction in the occurrence of head injury and the occurrence of fatal injury among the riders in that study. We found that helmets were associated with a 60% reduction in the risk of head injury ($p < 0.001$) and a 56% reduction of the risk of fatal injury (p 0.002).

Our new findings are generally consistent with the published literature. Liu et al. (2004) conducted a Cochrane review of motorcycle helmet literature and identified 16 studies that examined the association between helmet use and neck injury. Of the 16 studies, 14 reported no effect, one reported a protective effect, and one study, that of Goldstein, reported a deleterious effect. Our estimated risk ratio of 0.63 should be interpreted with caution given that most studies have not identified any significant association between helmet use and neck injury occurrence. In addition, our risk ratio estimate was borderline significant (p 0.044). Our result is consistent with the original findings reported by Hurt Study investigators, "...these sparse data do not confirm advantage or disadvantage to helmet use related to neck injury (Hurt et al., 1981a)."

Most studies, like ours, have also found beneficial effects of helmet use related to head injury and mortality. For example, NHTSA has estimated that motorcycle helmets reduce fatalities by 37% using data from the Fatality Analysis Reporting System (NHTSA, 2013). Norvell et al. (2002), using similar data, found that motorcycle helmets reduced the risk of fatal injury by 39% (RR 0.61, 95% CI 0.54–0.70) after accounting for age, sex, and numerous collision characteristics like motorcycle speed and collision severity. More recently, Crompton (2001) reported a fatality odds ratio of 0.75 (95% CI 0.65–0.86) for helmet use, after adjusting for multiple demographic and collision severity covariates. These findings, and most others, are roughly comparable to our estimated risk ratio of 0.44). Most research has also found that helmets are related to significant reductions in head injury occurrence, consistent with our findings. For example, Liu et al. (2004) combined the results of all head injury studies that controlled for confounders in their Cochrane Review to produce a pooled odds ratio of 0.41 (95% CI 0.21–0.81), which closely matches our risk ratio estimate of 0.40 (95% CI 0.31–0.52).

Our new analysis had several strengths. First, the ascertainment of helmet use in the Hurt Study used information from several sources and is likely to have accurately coded the helmet status of riders. Second, the injury information was obtained directly from medical providers or hospitals and was AIS-coded by consulting resident pathologists. Third, we used multivariate log-binomial regression to allow for the simultaneous control of numerous potential confounders of the helmet use-neck injury association. And, lastly, we analyzed the data using other regression approaches, including logistic, probit, and Poisson regression models, and found that no method produced results that were meaningfully different from those of our log-binomial models.

Our analysis was not without limitations. The identification and recruitment of motorcyclists during the Hurt Study may have been influenced by collision severity. For example, riders involved in very minor collisions may have been less likely to be included in the study. This selection may have affected the risk ratio estimation to an unknown degree because helmet effectiveness may vary by collision severity. In addition, some injuries, particularly minor ones, may have been overlooked and incorrectly coded as "no injury." However, bias in our risk ratio estimates would only result if the miscoding occurred differentially by helmet use, which seems unlikely.

5. Conclusions

The analysis reported by Goldstein in 1986 that has been heavily used by the anti-motorcycle helmet community as a justification for opposing mandatory helmet laws and helmet use was critically flawed. Goldstein fabricated values for a variable that was missing for 97.7% of riders. He also used an invalid method of summarizing overall neck injury severity. He used injury severity models that relied on very small numbers of riders with neck injury more severe than AIS 1 (minor), and he misinterpreted his model results.

Unfortunately, considerable damage has been done by this incorrect analysis and its spurious findings. The findings have been spread by anti-helmet groups and individuals over many years, and many motorcycle riders report that they are confident that motorcycle helmets cause neck injury. Our work with helmet exchange programs in California (where motorcyclists can exchange a novelty helmet for a better helmet) has taught us that many riders wear a novelty helmet because of their belief in a helmet-neck injury connection. We believe our paper sets the record straight on the association of helmets and neck injury and recommend that the Goldstein paper be retracted by *Evaluation Review*.

Any reasonable analysis of these data would have concluded that helmet use was strongly protective against fatal injury, strongly protective against head injury, and weakly to moderately protective against neck injury. Our analysis indicates that helmets reduced the occurrence of neck injury by an estimated 37% (p 0.044), head injury by 60% ($p < 0.001$), and fatal injury by 56% (p 0.002), after adjusting for age, sex, alcohol use, motorcycle speed, and most severe below-the-neck injury.

Acknowledgements

This project received support from a grant from the National Highway Traffic Safety Administration through the California Office of Traffic Safety (OTS-MC1501). David R. Thom and Terry Smith provided helpful comments.

References

American Association for Automotive Medicine, 1976. Abbreviated Injury Scale, 1976 Revision. Committee on Injury Scaling, American Association for Automotive Medicine, Morton Grove, IL.
Baker, S.P., et al., 1974. The Injury Severity Score: a method for describing patients with multiple injuries and evaluating emergency care. J. Trauma 14 (3), 187–196.
Barros, A.J., Hirakata, V.N., 2003. Alternatives for logistic regression in cross-sectional studies: an empirical comparison of models that directly estimate the prevalence ratio. BMC Med. Res. Methodol. 3, 21.
Bedi, I.S., 1987. An evaluation of the methodology and results of JP Goldstein's study, the effects of motorcycle helmet use on the probability of fatality and the severity of head and neck injuries. Eval. Rev. 11 (5), 670–677.
Crompton, J.G., 2001. Motorcycle helmets save lives, but not limbs: a National Trauma Data Bank analysis of functional outcomes after motorcycle crash. J. Surg. Res. 158 (1), 1–5.
Goldstein, J.P., 1986. The effect of motorcycle helmet use on the probability of fatality and the severity of head and neck injuries a latent variable framework. Eval. Rev. 10 (3), 355–375.
Greenland, S., et al., 1999. Causal diagrams for epidemiologic research. Epidemiology 10 (1), 37–48.
Hurt, H.H., et al., 1981a. Motorcycle Accident Cause Factors and Identification of Countermeasures: Volume I: Technical Report. Department of Transportation, Washington, DC, US.
Hurt, H.H., et al., 1981b. Motorcycle Accident Cause Factors and Identification of Countermeasures: Volume II: Appendix/Supplemental Data. Department of Transportation, Washington, DC, US.
Lawrence, B., et al., 2003. Costs of Injuries Resulting from Motorcycle Crashes: A Literature Review. National Highway Traffic Safety Administration, Washington, DC.
Little, R.A., 1992. Regression with missing X's: a review. J. Am. Stat. Assoc. 87 (420), 1227–1237.
Liu, B., et al., 2004. Helmets for preventing injury in motorcycle riders. Cochrane Database Syst. Rev., Cd004333.
Marsh, J.M., 1973. An occupant injury classification procedure incorporating the Abbreviated Injury Scale. Proceedings of the International Accident Investigation Workshop, National Highway Traffic Safety Administration.
McNutt, L., et al., 2003. Estimating the relative risk in cohort studies and clinical trials of common outcomes. Am. J. Epidemiol. 157 (10), 940–943.
NHTSA, 2013. Traffic Safety Facts, 2011 Data: Motorcycles. National Highway Traffic Safety Administration, Washington, DC.
Norvell, D.C., et al., 2002. Association of helmet use with death in motorcycle crashes: a matched-pair cohort study. Am. J. Epidemiol. 156 (5), 483–487.
Osler, T., et al., 1997. A modification of the injury severity score that both improves accuracy and simplifies scoring. J. Trauma 43 (6), 922–925, discussion 925–926.
Ouellet, J.V., et al., 1984. A system for coding detailed head and neck injury data. Proceedings of the 28th Conference of the American Association for Automotive Medicine.
Pigott, T.D., 2001. A review of methods for missing data. Educ. Res. Eval. 7 (4), 353–383.
StataCorp, 2014. Stata Statistical Software: Release 13. StataCorp, College Station, TX.
Vittinghoff, E., et al., 2012. Regression Methods in Biostatistics: Linear, Logistic, Survival, and Repeated Measures Models. Springer, New York.
Weiss, A.A., 1992. The effects of helmet use on the severity of head injuries in motorcycle accidents. J. Am. Stat. Assoc. 87 (417), 48–56.