Sex-based differences in helmet performance in bicycle trauma

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ABSTRACT

Objectives To determine the existence of sex-based differences in the protective effects of helmets against common injuries in bicycle trauma.

Methods In a retrospective cohort study, we identified patients 18 years or older in the 2017 National Trauma Database presenting after bicycle crash. Sex-disaggregated and sex-combined multivariable logistic regression models were calculated for short-term outcomes that included age, involvement with motor vehicle collision, anticoagulant use, bleeding disorder and helmet use. The sex-combined model included an interaction term for sex and helmet use. The resulting exponentiated model parameter yields an adjusted OR ratio of the effects of helmet use for females compared with males.

Results In total, 18 604 patients of average age 48.1 were identified, and 18% were female. Helmet use was greater in females than males (48.0% vs 34.2%, p<0.001). Compared with helmeted males, helmeted females had greater rates of serious head injury (37.7% vs 29.9%, p<0.001) despite less injury overall. In sex-disaggregated models, helmet use reduced odds of intracranial haemorrhage and death in males (p<0.001) but not females. In sex-combined models, helmets conferred to females significantly less odds reduction for severe head injury (p=0.002), intracranial bleeding (p<0.001), skull fractures (p=0.001), cranial surgery (p=0.006) and death (p=0.017). There was no difference for cervical spine fracture.

Conclusions Bicycle helmets may offer less protection to females compared with males. The cause of this sex or gender-based difference is uncertain, but there may be intrinsic incompatibility between available helmets and female anatomy and/or sex disparity in helmet testing standards.

BACKGROUND

Bicycling is an increasingly common activity, especially in urban centres. In the American Community Surveys, bicycling was the fastest growing mode of commuting between 2008 and 2012, increasing from 488 000 to 786 000 people.[1] New technologies such as e-bicycles, introduction of vehicle sharing and the expansion of dedicated infrastructure may alter rider demographics. Although bicycling has been a predominately male activity, these changes may lead to a greater representation of female riders. The introduction of electronically powered bicycles may increase bicycle trips in females to a greater degree than males.[2] Shared bicycles may be ridden by a greater proportion of female bicyclists than the community at large.[3] However, perceived safety is a motivator for cycling behaviour that may have a greater influence among females,[4] for which robust infrastructure is a critical element.[5 6]

Safety also emerges from effective protective equipment. Helmets reduce head injury in bicycle trauma,[7–10] even when the crash involves an automobile.[11] Although female sex has been associated with decreased odds of severe injury,[12–14] there has been no investigation of the relative benefit of bicycle helmets for females.

The National Trauma Data Bank (NTDB) has been used to demonstrate the general efficacy of helmets in preventing severe traumatic brain injury and death.[12 15] Although these analyses adjusted for sex, the role of sex in helmet efficacy was not discussed. We performed a retrospective cohort study of patients in the 2017 NTDB to assess for sex-based differences in helmet efficacy.

METHODS

Patients 18 years or older presenting after bicycle crash were identified in the 2017 NTDB using the International Classification of Diseases 10th Revision (ICD-10) codes for bicycle injuries. The NTDB includes records for patients presenting to several hundred participating hospitals within the USA within 14 days of a traumatic injury, excluding those with only superficial injuries. Data are extracted from clinical and administrative records of patient care. Demographics, helmet use, Injury Severity Scores (ISS) and short-term outcomes were extracted, and involvement in a motor vehicle collision (MVC),[16] injuries and procedures were identified by ICD-10 codes (online supplemental appendix 2). Abbreviated Injury Scale (AIS) scores were collected for head and below-the-neck body regions (body regions 4–8). 'Serious' injury was described as AIS >2. Analysis was performed in RStudio (V.1.2.5019, RStudio). Records' missing data on the patient sex were discarded. Summary statistics are given with the denominator as the total number of records with data for that variable, and the number of missing values was reported where greater than 0. Body mass index (BMI) contained outliers likely representing incorrectly formatted data. It was assumed there were no sex-based differences in this error. Exclusion of BMI from modelling changed model parameters by less than 5%.

Records were grouped by sex and helmet use. Descriptive statistics were performed using χ^2 testing for categorical variables and Welch's t-test for binary and continuous variables. Differences

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in proportion represented by a single group within a categorical variable were assessed by Fisher's exact test. Complete case analysis was used for modelling. Separate male and female multivariable logistic regression models of outcomes including normalised age, normalised BMI, helmet use and involvement in MVC as independent variables were calculated. A combined model was calculated with an interaction term for sex and helmet use. Independent variables were identified through review of similar studies. Model parameters were exponentiated and reported with 95% CIs and p values. The exponentiated regression parameter for the interaction term equals the ratio of the adjusted OR (aOR) for the outcome with helmet use for females over the same for males (aORR). Significance was defined as a two-sided p value <0.05.

Patient and public involvement

There were no funds or time allocated for patient and public involvement so we were unable to involve patients. We have invited patients to help us develop our dissemination strategy.

RESULTS

Summary statistics for demographics and outcomes are given in table 1. After excluding 62 cases because of missing sex data, there remained 18 604 cases of mean age 48 years, 18.0% of which were female. The majority of riders were white, with a greater proportion of white riders among females (84.1% vs 76.6%, p<0.001). The second most common single racial identity was black, with a lesser proportion among females (5.2% vs 10.7%, p<0.001).

Blood alcohol level (BAL) was less frequently reported and less frequently positive in females (47.9% vs 57.6%, 9.8% vs 20.4%, respectively, p<0.001). A smaller proportion of females had MVCs (32.2% vs 40.1%, p<0.001). Overall helmet use was 36.4% and was greater in females (39.4% vs 35.7%, p<0.001).

As reflected in the summative measures, females suffered less severe injuries. Mean ISS was lower in females (9.2 vs 10.6, p<0.001), as was the proportion of patients with ISS >15 (14.9% vs 19.9%, p<0.001). Serious arm and abdominal injuries were not significantly different between males and females, present in 28.5% and 3.7% of all patients, respectively. Presentations with emergency department Glasgow Coma Scale (GCS) <9, skull fractures and cervical spine fractures were also less common among females, though proportions of serious head injury by head AIS were not significantly different, overall 34.3%. Deaths were less frequent in females (1.3% vs 2.1%, p<0.001). Among all patients, the proportions of serious head injury and mortality were 34.3% and 1.9%, respectively.

Stratification by helmet use

For both sexes, unhelmeted riders were younger, less likely to be white and associated with MVC (table 2). The proportion of BAL testing reported was not different in females based on helmet use. For males but not females, unhelmeted patients more commonly had BAL tested (61.8% vs 50.1%, p<0.001). Among both female and male riders, a positive BAL test was more common in those without helmets (14.7% vs 2.1%, 27.3% vs 4.6%, p<0.001). MVCs were also more common in unhelmeted riders for both females and males (38.2% vs 22.9%, 47.4% vs 27.1%, p<0.001).

Helmet use improved measures of injury severity and proportions of head-specific injury for males but had a less universal effect in females. For both sexes, the mean ISS was nominally lower in unhelmeted patients (9.0 vs 9.5, 10.5 vs 10.8, p<0.001), and the percentage of patients with ISS >15 was unchanged. Proportions of serious abdominal injury were nominally higher in unhelmeted males, and proportions of serious arm injury were higher in both helmeted females and males (36.3% vs 23.9%, 37.7% vs 23.3%, p<0.001). In unhelmeted females and males, the proportion of patients with GCS <9 was significantly higher (4.4% vs 2.2%, 7.1% vs 3.0%, p<0.001). In females, the percentages of severe head injury (18.3% vs 13.6%, p<0.001) and skull fracture (10.2% vs 6.1%, p<0.001) were higher in unhelmeted patients, while cervical spine fractures were less common (4.5% vs 6.1%, p=0.042). Proportions of intracranial haemorrhage, cranial surgery and death were similar in helmeted and unhelmeted female riders. In male riders, proportions of all measures of head injuries were higher in unhelmeted patients except for cervical spine fractures, which were lower in unhelmeted patients (6.4% vs 9.9%).

Multivariable analysis

In the female-only model (online supplemental appendix 1, table 2), helmet use was associated with a protective effect against skull fracture (aOR 0.61 (0.46–0.81), p<0.001); but no change in the odds of intracranial bleeding, cranial surgery, ISS >15 or death. There was an increase in the odds of cervical spine fracture (aOR 1.5 (1.07–2.09), p=0.02), serious head injury (aOR 1.27 (1.08–1.49), p<0.001) and serious arm injury (aOR 1.83 (1.55–2.16), p<0.001) in the helmeted group. In the male-only model (online supplemental appendix 1, table 2), helmet use was associated with decreased odds of serious head injury (aOR 0.77 (0.71–0.83), p<0.001), intracranial haemorrhage (aOR 0.58 (0.52–0.64), p<0.001), skull fracture (aOR 0.36 (0.31–0.42), p<0.001), cranial surgery (aOR 0.66 (0.56–0.78), p<0.001) and death (aOR 0.44 (0.32–0.61), p<0.001); no change in ISS >15, and increased odds of cervical spine fracture (aOR 1.58 (1.38–1.8), p<0.001) and serious arm injury (aOR 2.02 (1.87–2.19), p<0.001). These effects are illustrated in figure 1.

In the sex-combined model (table 3), decreased odds of morbidity were associated with female gender and presence of a helmet. Female sex was associated with decreased odds of ISS >15 (aOR 0.75 (0.65–0.87), p<0.001), serious below-the-neck injury (aOR 0.76 (0.67–0.85), p<0.001), serious head injury (aOR 0.87 (0.78–0.97), p=0.01), skull fracture (aOR 0.81 (0.68–0.95), p=0.01), cervical spine fracture (aOR 0.7 (0.56–0.88), p<0.001), cranial surgery (aOR 0.73 (0.58–0.91), p=0.01) and death (aOR 0.64 (0.4–0.96), p=0.04), and no change in the odds of intracranial haemorrhage. Helmets were associated with decreased odds of severe head injury (aOR 0.77 (0.71–0.83), p<0.001), intracranial haemorrhage (aOR 0.57 (0.51–0.64), p<0.001), skull fracture (aOR 0.36 (0.31–0.42), p<0.001), cranial surgery (aOR 0.66 (0.56–0.78), p<0.001) and death (aOR 0.45 (0.32–0.62), p<0.001). Helmets were associated with no effect on ISS >15 and increased odds of serious below-the-neck injury (aOR 1.61 (1.49–1.73), p<0.001) and cervical spine fracture (aOR 1.60 (1.41–1.83), p<0.001).

The qualitative differences in helmet effects observed in the sex-disaggregated models were confirmed in the exponentiated sex–helmet interaction parameter in the combined model. There were significant aORRs for females and males in protection against serious head injury, serious below-the-neck injury, intracranial haemorrhage, skull fracture, cranial surgery and death. There was no sex-based difference in helmet effect for cervical spine fracture or ISS >15.

Table 1 Characteristics of injured bicyclists based on sex

	Male (n=15 252)	Female (n=3352)	Total (n=18 604)	P value
Age (years)	48.108 (16.242)	48.211 (15.901)	48.127 (16.181)	0.745
Race				<0.001
American Indian	85 (0.6%)	20 (0.6%)	105 (0.6%)	
Asian	377 (2.5%)	126 (3.8%)	503 (2.8%)	
Black	1593 (10.7%)	172 (5.2%)	1765 (9.7%)	
Other	1399 (9.4%)	197 (6.0%)	1596 (8.8%)	
Pacific Islander	35 (0.2%)	6 (0.2%)	41 (0.2%)	
White	11 423 (76.6%)	2763 (84.1%)	14 186 (78.0%)	
Missing	340	68	408	
BMI				<0.001
Mean (SD)	30.9 (62.3)	28.829 (38.2)	30.494 (58.695)	
Missing	2204	467	2671	
BAL result				<0.001
n (%)	1779 (20.2%)	160 (10.0%)	1939 (18.7%)	
Missing	6463	1746	8209	
Helmet use	5448 (35.7%)	1320 (39.4%)	6768 (36.4%)	<0.001
Motor vehicle collision	6117 (40.1%)	1079 (32.2%)	7196 (38.7%)	<0.001
GCS				<0.001
(0, 8)	826 (5.6%)	113 (3.5%)	939 (5.2%)	
(8, 13)	583 (4.0%)	94 (2.9%)	677 (3.8%)	
(13, 15)	13 349 (90.5%)	3008 (93.6%)	16 357 (91.0%)	
Missing	494	137	631	
ISS				<0.001
Mean (SD)	10.607 (8.686)	9.187 (7.642)	10.351 (8.524)	
Nmiss	24	5	29	
ISS >15				<0.001
n (%)	3024 (19.9%)	500 (14.9%)	3524 (19.0%)	
Nmiss	24	5	29	
Head AIS >2				0.836
n (%)	5221 (34.2%)	1153 (34.4%)	6374 (34.3%)	
Nmiss	4	3	7	
Abdominal AIS >2				0.123
n (%)	544 (3.6%)	138 (4.1%)	682 (3.7%)	
Nmiss	4	3	7	
Arm AIS >2				0.680
n (%)	4335 (28.4%)	964 (28.8%)	5299 (28.5%)	
Nmiss	4	3	7	
Skull fracture	1585 (10.4%)	288 (8.6%)	1873 (10.1%)	0.002
Intracranial haemorrhage	2315 (15.2%)	530 (15.8%)	2845 (15.3%)	0.356
Cervical spine fracture	1172 (7.7%)	171 (5.1%)	1343 (7.2%)	<0.001
Cranial surgery	943 (6.2%)	169 (5.0%)	1112 (6.0%)	0.012
Death	312 (2.0%)	43 (1.3%)	355 (1.9%)	0.003

AIS, Abbreviated Injury Scale; BAL, blood alcohol level; BMI, body mass index; GCS, Glasgow Coma Scale; ISS, Injury Severity Score.

DISCUSSION

These findings recapitulate that helmets protect against head injury and death in bicycle trauma but also suggest that helmets may be less effective among traumatically injured females. The overall protective effects of bicycle helmets correspond well with published data from meta-analysis which range from 0.31 to 0.42 for serious head injury and from 0.27 to 0.35 for fatality,[7–10] compared with 0.48 and 0.34 in this study. Recent meta-analyses have disagreed over the effect of helmet use on neck injury. Elvik reported a summary OR of neck injury of 1.28,[8] but a more recent review by Olivier and Creighton has suggested that there is no increased risk of neck injury.[9] This discrepancy might be by a difference in the definition of 'neck injury'—which would include a broad set of injuries—from cervical spine fracture. Regardless, Olivier and Creighton note the relative infrequency and non-severity of neck injuries compared with head injuries,[9] which is supported by the data in this study. Proportions of intracranial bleeding were roughly twice that of cervical spine fractures. Nonetheless, our findings support the need for biomechanical investigations of this phenomenon.

Table 2 Characteristics of injured bicyclists stratified by sex and helmet use

	Male			Female		
	No helmet (n=9804)	Helmet (n=5448)	P value	No helmet (n=2032)	Helmet (n=1320)	P value
Age (years)	46.0 (16.3)	51.915 (15.4)	<0.001	46.6 (16.6)	50.6 (14.5)	<0.001
Race			<0.001			<0.001
American Indian	68 (0.7%)	17 (0.3%)		17 (0.9%)	3 (0.2%)	
Asian	207 (2.2%)	170 (3.2%)		72 (3.6%)	54 (4.2%)	
Black	1440 (15.1%)	153 (2.9%)		146 (7.3%)	26 (2.0%)	
Other	1075 (11.3%)	324 (6.0%)		147 (7.4%)	50 (3.9%)	
Pacific Islander	23 (0.2%)	12 (0.2%)		5 (0.3%)	1 (0.1%)	
White	6736 (70.5%)	4687 (87.4%)		1605 (80.6%)	1158 (89.6%)	
Missing	255	85		40	28	
BMI			<0.001			<0.001
Mean (SD)	31.9 (62.1)	29.1 (627)		30.5 (43.1)	26.4 (29.0)	
Missing	1489	715		297	170	
BAL result			<0.001			<0.001
n (%)	1654 (27.3%)	125 (4.6%)		147 (14.7%)	13 (2.1%)	
Missing	3746	2717		1032	714	
Motor vehicle collision	4643 (47.4%)	1474 (27.1%)	<0.001	777 (38.2%)	302 (22.9%)	<0.001
GCS			<0.001			0.001
(0, 8)	669 (7.1%)	157 (3.0%)		85 (4.4%)	28 (2.2%)	
(8, 13)	473 (5.0%)	110 (2.1%)		63 (3.3%)	31 (2.4%)	
(13, 15)	8313 (87.9%)	5036 (95.0%)		1786 (92.3%)	1222 (95.4%)	
Missing	349	145		98	39	
ISS			<0.001			<0.001
Mean (SD)	10.513 (9.239)	10.776 (7.589)		9.012 (7.885)	9.456 (7.247)	
Nmiss	21	3		5	0	
ISS >15			0.061			0.906
n (%)	1987 (20.3%)	1037 (19.0%)		304 (15.0%)	196 (14.8%)	
Nmiss	21	3		5	0	
Head AIS >2			<0.001			0.001
n (%)	3593 (36.7%)	1628 (29.9%)		655 (32.3%)	498 (37.7%)	
Nmiss	4	0		3	0	
Abdominal AIS >2			0.002			0.775
n (%)	383 (3.9%)	161 (3.0%)		82 (4.0%)	56 (4.2%)	
Nmiss	4	0		3	0	
Arm AIS >2			<0.001			<0.001
n (%)	2280 (23.3%)	2055 (37.7%)		485 (23.9%)	479 (36.3%)	
Nmiss	4	0		3	0	
Skull fracture	1316 (13.4%)	269 (4.9%)	<0.001	207 (10.2%)	81 (6.1%)	<0.001
Intracranial haemorrhage	1711 (17.5%)	604 (11.1%)	<0.001	331 (16.3%)	199 (15.1%)	0.347
Cervical spine fracture	632 (6.4%)	540 (9.9%)	<0.001	91 (4.5%)	80 (6.1%)	0.042
Cranial surgery	704 (7.2%)	239 (4.4%)	<0.001	103 (5.1%)	66 (5.0%)	0.929
Death	255 (2.6%)	57 (1.0%)	<0.001	27 (1.3%)	16 (1.2%)	0.769

AIS, Abbreviated Injury Scale; BAL, blood alcohol level; BMI, body mass index; GCS, Glasgow Coma Scale; ISS, Injury Severity Score.

The most concerning finding in this investigation is the increased proportion of serious head injuries among helmeted females compared with helmeted males in spite of decreased proportions of MVC, intoxication and wholistic measures of injury severity. The latter finding is consistent with other reports which have shown decreased risk of injury or mortality in female bicyclists,[13 17] although other reports have demonstrated null effect[18] or even increased risk.[19] This effect was also evidenced in multivariate modelling, although this analysis is limited by the comparison of helmeted with unhelmeted riders, which will be discussed. Nonetheless, our findings suggest that women who wear helmets do not have the same degree of protection from severe head injuries as male counterparts.

Explanations of the effects of sex or gender have ranged from anatomical differences to differences in on-road behaviour that might change crash energy and severity. Regarding the latter, a US study of rider route choice showed risk-aversive route selection among females, preferring lower speed limit routes with fewer cars and slopes.[20] This finding has been duplicated among British cyclists.[6] A German study showed less frequent intoxication

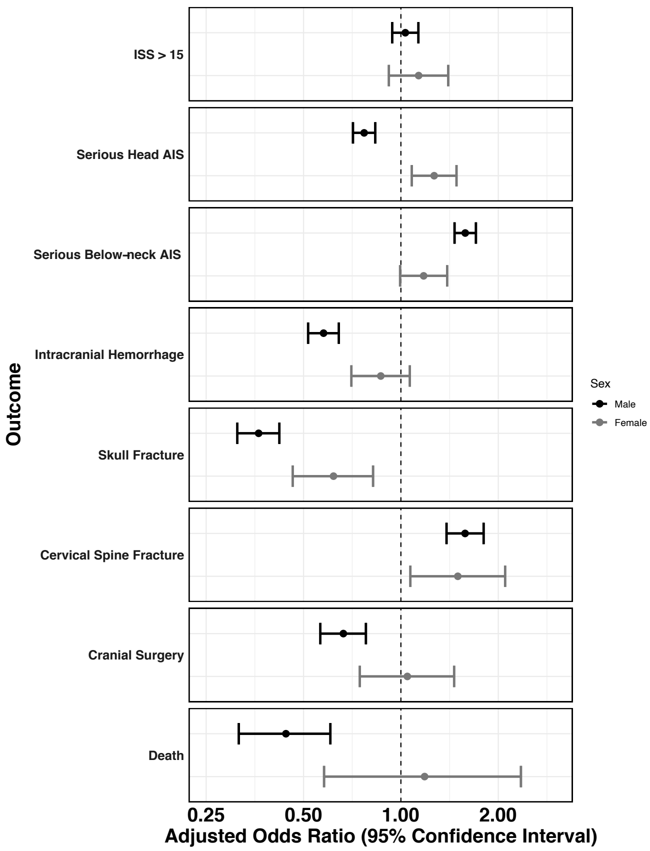

Figure 1 Effects of helmet use on various outcomes in sex-segregated multivariate models. AIS, Abbreviated Injury Scale; ISS, Injury Severity Score.

among injured female riders,[21] consistent with our findings. An Italian study suggests a complex relationship between different types of risk behaviour and sex in which sex increases some types of risky behaviours and decreases others.[22] Prior research has shown a mix of increased[16 18 23] and null effects[24] on head injury associated with collision with a motor vehicle with both vehicle speed and direction of impact implicated in mortality.[18 25] Sex-based differences in on-road behaviour may potentiate these differences. To facilitate comparisons between sexes in the face of this complexity, BMI and MVC were included in modelling.

Alternatively, helmet design and testing may be biased towards males. This reasoning is not novel, with recent investigations of automobile safety revealing increased risk of injury and death for female occupants. Authors speculated that the increased risk for injury in female passengers arose from sex-based biometric variation that decreased the efficacy of safety features.[26 27] One study reported a 47% greater odds of a severe injury for females when controlling for age, mass, BMI category and crash characteristics. The authors attributed this effect to a male bias in vehicle safety testing standards which depend largely on a 50th percentile male crash test dummy and, to a lesser degree, a 5th percentile female crash test dummy—a scaled down version of the male model.[28] We were unable to find similar investigations into the testing design of bicycle helmets or any other type of helmet.

In bicycle helmets, this phenomenon may manifest in fit. In children, poorly fit helmets were associated with almost twice the risk of head injury compared with well-fit helmets.[29] In one study of helmet fit, females were 1.9 times more likely to wear an incorrectly adjusted helmet. Though females were more likely to wear a correctly sized helmet, the authors showed that stability (resistance to rotation around the head) depended on proper adjustment but not correct size.[30] A study using MRI data to create parametrised head anatomy models demonstrated sex-based differences in averaged head morphology, with the greatest differences in the supraorbital ridge. The study also showed that parametrised head forms created from MRI data that include male heads yielded models that fit female anatomy more poorly than models created from female-only MRI scans, with the greatest error in the forehead,[31] which may be an important point of contact for a bicycle helmet. Finally, a quantitative evaluation of helmet fit using 3D scanning of head anatomy identified that females had a lower quality of fit assessed against a set of commercially available helmets.[32] We interpret these findings to mean that sex-specified head forms used in design and testing may improve fit and therefore safety and efficacy of the helmet.

Table 3 Adjusted ORs for all model parameters for outcomes in sex-combined multivariable regression

Outcome	Female/helmeted interaction, aORR (95% CI)	Female, aOR (95% CI)	Helmet use, aOR (95% CI)	Normalised BMI, aOR (95% CI)	Normalised age, aOR (95% CI)	Motor vehicle collision, aOR (95% CI)
ISS >15	1.06 (0.84 to 1.32), p=0.64	0.75 (0.65 to 0.87), p<0.001	1.04 (0.95 to 1.14), p=0.41	1 (0.96 to 1.04), p=0.97	1.01 (1.01 to 1.01), p<0.001	2.11 (1.94 to 2.29), p<0.001
Serious below-the-neck injury	0.70 (0.58 to 0.83), p<0.001	0.76 (0.67 to 0.85), p<0.001	1.61 (1.49 to 1.73), p<0.001	0.98 (0.94 to 1.01), p=0.25	1.02 (1.02 to 1.02), p<0.001	1.23 (1.15 to 1.32), p<0.001
Serious head injury	1.68 (1.41 to 1.99), p<0.001	0.87 (0.78 to 0.97), p=0.01	0.77 (0.71 to 0.83), p<0.001	1.01 (0.97 to 1.04), p=0.69	1 (1 to 1.01), p=0.01	1.36 (1.27 to 1.46), p<0.001
Intracranial haemorrhage	1.56 (1.24 to 1.97), p<0.001	0.95 (0.83 to 1.09), p=0.46	0.57 (0.51 to 0.64), p<0.001	1.03 (0.99 to 1.06), p=0.14	1.01 (1.01 to 1.02), p<0.001	1.43 (1.31 to 1.57), p<0.001
Skull fracture	1.68 (1.22 to 2.3), p=0	0.81 (0.68 to 0.95), p=0.01	0.36 (0.31 to 0.42), p<0.001	0.97 (0.89 to 1.03), p=0.44	0.99 (0.99 to 1), p<0.001	1.5 (1.35 to 1.67), p<0.001
Cervical spine fracture	0.88 (0.62 to 1.24), p=0.46	0.69 (0.54 to 0.88), p<0.001	1.6 (1.41 to 1.83), p<0.001	0.96 (0.85 to 1.03), p=0.38	1.01 (1.01 to 1.01), p<0.001	1.56 (1.38 to 1.76), p<0.001
Cranial surgery	1.6 (1.11 to 2.29), p=0.01	0.73 (0.58 to 0.91), p=0.01	0.66 (0.56 to 0.78), p<0.001	1.02 (0.96 to 1.06), p=0.36	0.99 (0.99 to 1), p<0.001	1.14 (1 to 1.3), p=0.05
Death	2.2 (1.03 to 4.58), p=0.04	0.64 (0.4 to 0.96), p=0.04	0.45 (0.32 to 0.62), p<0.001	1 (0.85 to 1.07), p=0.97	1.03 (1.02 to 1.04), p<0.001	3.38 (2.63 to 4.38), p<0.001

aOR, adjusted OR; aORR, adjusted OR ratio; BMI, body mass index; ISS, Injury Severity Score.

Evolving trauma demographics make urgent the need for improved protection for female riders. Early reports of injuries associated with shared vehicle use suggest higher proportions of female riders. For example, the proportion of females among injured e-scooter riders ranged from 35% to 55%[33–35] in US cities. Despite the dismally poor utilisation of helmets reported in these studies—ranging from 0% to 4.4%—bicycle helmet use is recommended for e-scooter riders by the US Consumer Product Safety Commission,[36] and, insofar as they will be used equally, a greater number of them will protect female riders.

Serious below-the-neck injuries were identified as a form of experimental validation; one would not expect changes to them based on helmet use. Nonetheless, serious below-the-neck injuries were less common among unhelmeted riders, possibly representing a dilution by isolated head injuries. Alternatively, helmeted riders might evidence 'risk-compensation' where they exhibit riskier behaviour. This hypothesis is not supported, however, by the lower rate of MVC and intoxication in the helmeted group. Furthermore, a recent systemic review has found little evidence for this hypothesis.[37] Regardless, the effect existed among both sexes, so its effect on comparative analyses may be blunted.

This variation and the findings of our sex-segregated models highlight the flaws intrinsic to a common method for validating the protective effect of helmets across the population, comparing injured helmet patients to injured unhelmeted patients. There are likely unaccounted differences between these groups that confound the analysis This approach failed to show a protective effect against death and serious head injury in an important subgroup—females. In no uncertain terms, we endorse that helmets are effective and recommend their use for the whole population. However, multivariate analysis that 'accounts' for sex in a predominately male patient population has obscured an opportunity to improve safety for a large swath of the population, and such analyses should be treated cautiously.

There are important limitations to this approach. First, 'sex' was specified in the database, but behavioural differences that contribute to observed effects might better attribute to gender, which was not documented. For example, hair style, which may be a gendered attribute, might impact helmet fit. Second, because of the abstracted nature of the data, sex-based bias in reporting cannot be evaluated. Similarly, prior research of bicycle-related trauma has shown that alcohol intoxication is independently correlated with more severe injury,[38] but these data were missing in over 40% of records and could not be included in modelling.

Finally, the exclusion criteria of the NTDB limit the generalisability of findings. Patients with only superficial injuries or those not presenting to medical attention are excluded and theoretically include patients successfully protected from serious head injury by a helmet. The effect of this is likely underestimating the protective effects of helmet. Patients who die at the scene of a bicycle accident may also be excluded. In 2017, 88% of all fatally injured bicyclists regardless of presentation to hospital were male,[39] equivalent to the proportion in this study. For all these reasons, our findings are exploratory in nature and should be validated with further anatomical and clinical studies.

With the growing popularity of bicycling and related transport modes, the need for effective protective devices including helmets is urgent. Ensuring equity across all riders is paramount. The design, testing and research of helmets span many fields including public, corporate and academic entities. Our findings support the need to examine these processes for structural biases that contribute variation in helmet efficacy. How they emerge from social, behavioural or anatomical variation remains unclear and requires further research. With these conclusions in mind, we also note that our findings evidence foremost that health outcome disparities have complex mechanisms emerging across numerous environmental features. There exist extensive and growing literatures documenting the protective effects of and social disparities manifest in other environmental factors including transit infrastructure, rider education and more. None of these can be forgotten as important targets in eliminating disparity and improving the safety of all vulnerable road users.

What is already known on this subject

- Helmets are protective against cranial injury in bicycle trauma.
- Though bicycle trauma has been disproportionately male, new bicycle infrastructures are increasing female ridership.

What this study adds

- Helmet use was greater among females than males.
- Helmets decreased the odds of intracranial haemorrhage and death in males but not in females; the odds of serious head injury were decreased in males and increased in females who wore helmets.
- Helmets reduced the odds of intracranial haemorrhage, skull fracture, cranial surgery and death to a lesser degree in females than males.

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