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Original article

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Bicycle injuries and helmet use: a systematic review and meta-analysis

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Abstract

Background: The research literature was systematically reviewed and results were summarized from studies assessing bicycle helmet effectiveness to mitigate head, serious head, face, neck and fatal head injury in a crash or fall.

Methods: Four electronic databases (MEDLINE, EMBASE, COMPENDEX and SCOPUS) were searched for relevant, peer-reviewed articles in English. Included studies reported medically diagnosed head, face and neck injuries where helmet use was known. Non-approved helmets were excluded where possible. Summary odds ratios (OR) were obtained using multivariate meta-regression models stratified by injury type and severity. Time trends and publication bias were assessed.

Results: A total of 43 studies met inclusion criteria and 40 studies were included in the meta-analysis with data from over 64 000 injured cyclists. For cyclists involved in a crash or fall, helmet use was associated with odds reductions for head (OR = 0.49, 95% confidence interval (CI): 0.42–0.57), serious head (OR = 0.31, 95% CI: 0.25–0.37), face (OR = 0.67, 95% CI: 0.56–0.81) and fatal head injury (OR = 0.35, 95% CI: 0.14–0.88). No clear evidence of an association between helmet use and neck injury was found (OR = 0.96, 95% CI: 0.74–1.25). There was no evidence of time trends or publication bias.

Conclusions: Bicycle helmet use was associated with reduced odds of head injury, serious head injury, facial injury and fatal head injury. The reduction was greater for serious or fatal head injury. Neck injury was rare and not associated with helmet use. These results support the use of strategies to increase the uptake of bicycle helmets as part of a comprehensive cycling safety plan.

Key words: Cycling, injury, helmet, meta-analysis, systematic review

Key messages

- This is the largest ever systematic review and meta-analysis of bicycle injury and helmet use, with over 64 000 injured cyclists from 40 studies.
- Bicycle helmet use was associated with reductions in head, serious head, face and fatal head injury.
- Reductions were greater for serious injury than for injuries of any severity.
- Neck and diffuse axonal injury were rare among cyclists and were not associated with helmet use.

Introduction

Cycling is a healthy activity and can be an efficient form of transport; however, cycling is not without risk. Bicycle crashes and falls are rare, but they can cause a range of injuries from minor to permanent disability or fatality. A recent Australian cohort study of adult cyclists estimated 0.29 crashes per 1000 km cycled (95% CI: 0.26–0.32), with cyclists seeking medical treatment in 8% of these crashes.[1] Head injuries, in particular, are an important fraction of cycling-related injuries. In a recent Australian study of linked police and hospital data for cyclists in motor vehicle collisions, 34% of hospital-admitted cyclists had a head injury and 15% had a serious head injury.[2] In a coroner's review of cycling fatalities in Canada, 55% of deaths were caused by head injuries.[3]

Bicycle helmets are designed for head protection in the event of a fall or crash.[4] Research into helmet effectiveness to mitigate cycling head injury has primarily consisted of case-control and population-based studies. Alternative study designs include laboratory testing of helmet performance in dummy crash tests and computer simulation.[5–8] Randomized controlled trials in this area are not possible due to ethical considerations.

The first large, case-control study of helmet effectiveness found very large protective effects, estimating 85% and 88% reductions in head and brain injury, respectively, for helmeted cyclists relative to unhelmeted cyclists.[9] Later studies have also found protective effects, but not often to the same extent. For example, a recent case-control study in France found risk reductions of 24–31% (depending on adjustment methods) for head injury and 70% for head injuries greater than 2 on the Abbreviated Injury Scale (AIS).[10]

In addition to head injuries, previous researchers have investigated whether helmet use is associated with face or neck injuries.[11,12] In particular, a recent review found helmet use was protective for upper and middle facial injuries;[13] the evidence is mixed with regards to neck injuries, although the incidence of such injuries is uncommon.[14,15] If helmet use is associated with head, face or neck injuries, then cyclists with any such injuries should be excluded from the control group. Otherwise, the use of other injuries may not be a valid control group.[10,16] In practice, very few studies limit controls to those injured below the neck.

There have been two systematic reviews with meta-analysis published on case-control studies of bicycle helmet effectiveness.[11,17] Both reviews concluded that helmets are effective at reducing head injury in a crash, although they differ with regards to inclusion criteria and their estimates of effectiveness. In a Cochrane Review, Thompson *et al.*[17] included studies that collected data prospectively, injuries were medically verified and analyses controlled for selection bias, observational bias or confounding. Attewell *et al.*,[11] on the other hand, did not exclude on the basis of study design and only required studies report data for a 2×2 cross-classification table of helmet use and injury. Additionally, both reviews included studies reporting head, brain or facial injury, and Attewell and colleagues also included neck and fatal injury. With regards to helmet effectiveness, Thompson and colleagues estimated that helmet use is associated with reductions of 63–88% in head, brain or severe brain injury. Attewell and colleagues estimated more conservative reductions of 60% for head injury and 58% for brain injury.

A more recent meta-analysis was performed by adding four studies to the Attewell *et al.* review for head, face and neck injuries only.[12,18] Elvik, in a re-analysis of previous reviews, identified publication and trend bias and he indicated that the authors of the Cochrane review have conflicts of interest as they co-authored four of the seven included studies. He also identified publication bias and time trend bias as affecting the summary estimates. Using the trim-and-fill method to adjust for publication bias,[19] Elvik reported that helmet use was associated with a 50% reduction in head injury and a 21% reduction in face injury. He also found helmet use increased the odds of neck injury by 28% with no adjustment for publication bias. Additionally, Elvik combined effect sizes for head, face and neck injury into one analysis while again adjusting for publication bias using the trim-and-fill method. He reported that helmet use was associated with a 33% reduction in injury to the head, face or neck.

Elvik's meta-analysis could also be improved. For example, the assessment of publication bias requires an independent review of the research literature by two authors, and this is not possible when there is a sole author. Further, the protective effect for head, face and neck injuries were assumed to be identical, although there is no evidence that helmets affect different injuries in the same manner. Importantly, such heterogeneity among effect sizes for different body locations could be the cause of funnel plot asymmetry, and not publication bias. Third, the use of the trim-and-fill method to adjust for publication bias is usually not recommended.[20–22] Terrin *et al.*[22] demonstrated that trim-and-fill adjustment can underestimate the true effect size when there is no publication bias, and Simonsohn *et al.*[21] found that this method does not generally correct for publication bias when it does exist. Additionally, the journal published two full-length corrections due to data and analytical errors.[12,23]

In sum, the research literature on bicycle helmet effectiveness was last systematically reviewed by Attewell and colleagues in 1999, and past reviews have been criticized for methodological weaknesses and did not account for sources of bias. Therefore, the objective of this study was to conduct an updated systematic review and meta-analysis of studies that assess whether helmet use mitigates head, serious head, face, neck and fatal head injury. If publication or time trend bias is detected, appropriate adjustment methods will be used.

Methods

In accordance with study protocol (unpublished, available from first author), four electronic databases (MEDLINE, EMBASE, COMPENDEX and SCOPUS) were searched to identify relevant articles. An initial search was performed on 2 February 2015, which was updated 26 January 2016. Broad search terms were used (helmet* AND (cycl* OR bicycle*)), to include as many studies as possible. Full-text, English language studies were included if injuries were medically diagnosed (i.e. self-reported injury data were excluded), helmet status was known and data were available to construct a 2×2 table of injury by helmet status. When two or more studies include data from the same source, the study with the most complete data was included. Study authors were contacted if relevant data were not published but the study met other criteria. When published abstracts met other inclusion criteria, a search was conducted for a full-text report of the study and the authors were contacted. The two study authors independently searched/assessed articles against inclusion criteria and extracted data with adherence to the PRISMA statement.[24] Conflicts were resolved through discussion. A research librarian was consulted before the search for articles.

The data were categorized as relating to head, serious head, face, neck or fatal head injuries. Head, face or neck injuries were of any severity. Studies that reported cyclists with AIS3+ head injuries, skull fractures, intracranial haemorrhage, intracranial injury, loss of consciousness, survival risk ratio less than 0.965 or head injuries reported as 'serious', 'severe' or 'brain' injury were classified as serious head injury. Concussions in isolation were not considered serious head injuries, as they are usually less than AIS3.[25] The categorization of serious head injury is approximately equivalent to 'brain injury' from past reviews.[11,17] Studies reporting fatalities were included if injured body regions were reported. Cycling fatalities with multiple injuries including the head were categorized as a head injury. Whenever possible, cyclists wearing unapproved, no shell, foam or leather helmets were excluded and controls were limited to those injured solely below the neck. The information extracted from each study included the number of injured cyclists available for analysis, the number of cases and controls by helmet use, the country where data were collected, whether the data were collected prospectively or retrospectively, age categories of cyclists included (all, child or adult), the proportion of missing helmet data, the proportion of males, the proportion of motor vehicle collisions and whether injuries to the head, face or neck were included in the controls.

A series of hierarchical random effects meta-regression models were fit for the log odds ratio using all extracted data. Before analysis, 0.5 was added to each cell when no injuries were reported in any 2×2 table. Model 1 was a baseline model with no moderators, Model 2 included injury type as a moderator, Model 3 included a random effect for study and Model 4 included a random effect for injury type. The final model was chosen by the likelihood ratio test and Akaike's information criterion (AIC). The use of multivariate meta-regression methods allows the analysis to consider the injured cyclist as a whole as opposed to individual body regions.

Residual heterogeneity was assessed by Cochran's Q statistic and the index of heterogeneity I^2. Publication bias was inspected visually using funnel plots and formally tested using the rank correlation test. Time trend bias was inspected visually using cumulative forest plots and formally tested by including year as a covariate (centred at 2016, the year of the last included study). All statistical analyses were performed using the R metafor package.[20] The data file and an R markdown file that performs all analyses are available as supplementary material (available as Supplementary data at *IJE* online).

Results

The flow diagram for reviewed studies is given in Figure 1. The literature search produced 2405 total results of which

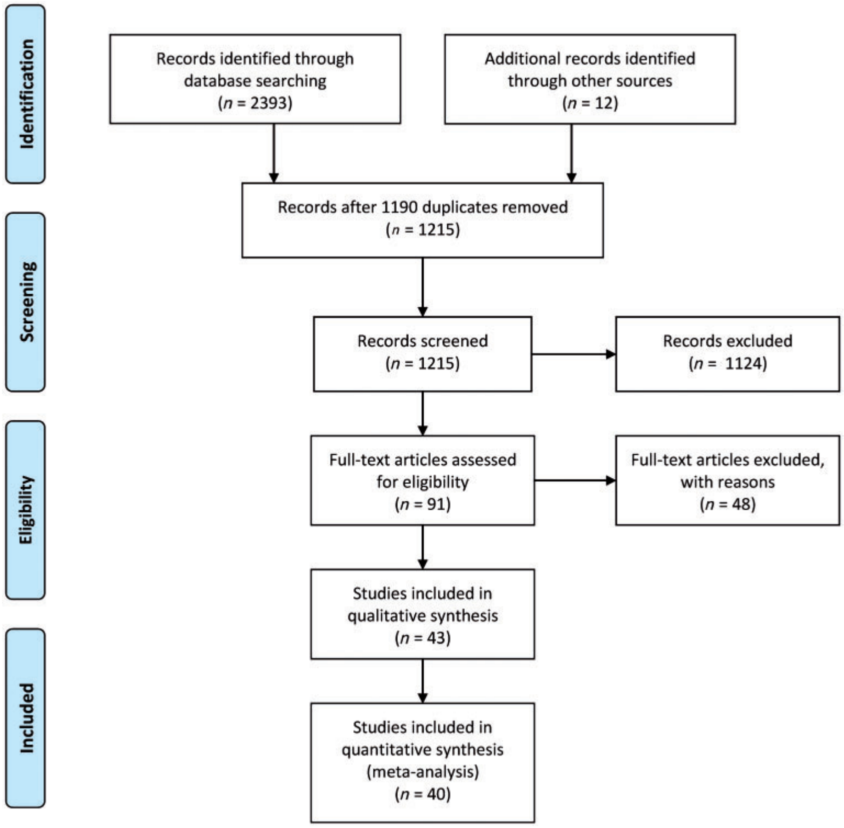

Figure 1. PRISMA flow diagram of included studies.

1190 were duplicates. A title and abstract search eliminated a further 1125 records; 91 full-text articles were assessed for eligibility and 48 studies did not meet study criteria. The primary reasons for exclusion were: the inability to construct a 2×2 table of injury by helmet status;[26–43] the study data were a subset of data used in an included study;[44–53] collected data were a case series;[54–60] injuries were self-reported;[61–65] the published report was an abstract only;[66–69] helmet data were unreliable;[70,71] and there was conflicting information in the paper.[72,73] A further three studies were not included in a meta-analysis as there were too few helmeted cyclists to reliably estimate odds ratios.[74–76] The 40 studies included in the meta-analysis comprised 64 708 injured cyclists and 89 total effect sizes (28 head, 30 serious head, 17 face, 12 neck and 2 fatal head injuries). By contrast, the most recent review by Elvik included data on 19 580 cyclists from 20 studies.

Characteristics of the studies included for the meta-analysis are given in Table 1. The included studies span 28 years (1989–16) representing four continents (Asia: 2, Australia: 9, Europe: 8, North America: 21); 26 studies reported multiple injury types; and only 14 studies limited controls to injuries below the neck. Data were collected prospectively in 23 studies and retrospectively in 17. The reported injuries were diagnosed in: an emergency department or trauma centre ($n = 23$); a hospital which may include emergency or trauma data ($n = 9$); an injury or trauma database ($n = 6$); or coronial reports ($n = 2$). Although most studies reported cycling injuries for all ages ($n = 24$), some studies reported injuries solely for children ($n = 10$) or adults ($n = 6$). Across all studies, males were more common than females (75%, range: 48–90%) and collisions with motor vehicles varied greatly (31%, range: 3–100%, $n = 8$ studies missing data).

The results from the random effects meta-analysis models are given in Table 2. Model 4 was chosen as the final model which includes injury type as a moderator and random effects for injury type by study. The inclusion of each model component greatly improved model fit. Study-level moderators for continent where data were collected, setting for data collection, prospective or retrospective data collection, an indicator for mandatory helmet legislation for data collection jurisdiction, age category, proportion of males and proportion of cyclists in a motor vehicle collision were individually added to Model 4. None of these moderators improved model fit or substantially modified estimates of helmet effectiveness by injury type.

There was no strong evidence of publication bias in the overall model ($\tau = -0.08$, $P = 0.25$) or the funnel plot of the model residuals (see Figure 2). There is some asymmetry

Table 1. Characteristics of studies meeting selection criteria

Authors	Publication Year	Country	Study Size[a]	Age	Head	Serious Head	Face	Neck	Fatal	Control Excludes	SH
Thompson *et al.*[9]	1989	USA	668	All	X	X				H	AIS2+[c]
Thompson *et al.*[109]	1990	USA	531	All			X			H, F	
Spaite *et al.*[77]	1991	USA	284	All		X				SH	ICH, SF
Cooke *et al.*[110]	1993	Australia	35	All					X	H, F, N	
McDermott *et al.*[14]	1993	Australia	1710	All	X	X	X	X		C	AIS3+
Maimaris *et al.*[104]	1994	UK	1042	All		X				H, F, N	
Thomas *et al.*[111]	1994	Australia	364	Child	X	X	X			H, F	LOC
Li *et al.*[112]	1995	USA/Can	1538	Child		X				SH	ICI, SF
Finvers *et al.*[113]	1996	Canada	699	Child		X[b]				SH	ICH, SF, C
Thompson *et al.*[114]	1996	USA	3390	All	X	X				H	ICI, C
Thompson *et al.*[115]	1996	USA	3388	All			X			H, F	
Rivara *et al.*[15]	1997	USA	3384	All				X		N	
Jacobson *et al.*[116]	1998	Australia	229	All	X[b]					H	
Linn *et al.*[117]	1998	Canada	1462	Child	X[b]	X				H, F	B
Shafi *et al.*[118]	1998	USA	208	Child	X	X				H	ICI
Borglund *et al.*[119]	1999	USA	125	Child	X[b]	X				H	ICH, SF
Hansen *et al.*[120]	2003	Norway	991	All	X		X			H, F, N	
Heng *et al.*[78]	2006	Singapore	160	All	X	X	X			C	ICH
Airaksinen *et al.*[84]	2010	Finland	151	All	X[b]					H, F	
Dinh *et al.*[107]	2010	Australia	287	Adult		X				C	ICH, SF
Sze *et al.*[85]	2011	Hong Kong	682	All	X	X	X			H, F, N	AIS3+
Amoros *et al.*[10]	2012	France	8373	All	X	X	X	X		H, F, N	AIS3+
Crocker et al.[121]	2012	USA	420	Adult	X	X				H	B
Persaud *et al.*[3]	2012	Canada	129	All					X	H	
Wagner *et al.*[105]	2012	USA	163	Adult	X	X	X			H, F, N	AIS3+
Bambach *et al.*[2]	2013	Australia	6745	All	X	X				H	SRR ≤ 0.965
Dinh *et al.*[86]	2013	Australia	110	Adult	X	X	X			H, F, N	AIS3+
McIntosh et al.[25]	2013	Australia	137	All	X	X		X		C	AIS3+
Webman *et al.*[87]	2013	USA	374	All	X	X	X	X		H, F, N	AIS3+
Hooten *et al.*[88]	2014	USA	249	All				X		N	
Lindsay & Brussoni[89]	2014	Canada	15569	Child	X	X	X	X		H, F, N	ICI
Malczyk *et al.*[97]	2014	Germany	543	All	X[b]	X[b]				H, F	AIS3+
Otte & Wiese[106]	2014	Germany	245	All	X	X				H, F	AIS3+
Zibung *et al.*[90]	2014	Sweden	186	Adult	X	X	X	X		H, F, N	ICH
Dinh *et al.*[91]	2015	Australia	4245	Adult	X	X	X			H, F, N	AIS2+
Gulack *et al.*[92]	2015	USA	7678	Child	X[b]	X[b]		X		C	AIS3+
Harada *et al.*[122]	2015	USA	505	All		X[b]				C	AIS3+
Kaushik *et al.*[93]	2015	USA	567	Child	X[b]	X[b]				H, F, N	B
Sethi *et al.*[94]	2015	USA	699	All	X	X	X	X		H, F, N	AIS3+
Olofsson *et al.*[95]	in press	Sweden	3711	Child	X	X	X			H, F, N	AIS3+

C, Cases; F, Face; H, Head; N, Neck; SH, serious head injury; AIS, Abbreviated Injury Scale; B, Brain; C, Concussion; ICH, Intracranial haemorrhage; ICI, Intracranial injury; LOC, Loss of consciousness; SF, Skull fracture; SRR, Survival risk ratio; Can, Canada.

[a]Number of cyclists available for analysis.

[b]Includes facial injuries.

[c]Excludes cyclists with skull fractures only or without loss of consciousness.

from three effect sizes taken from two small sample studies and which therefore have little statistical weight in the analysis.[77,78] There was no evidence of time trends when year was included in the overall model ($P = 0.68$).

A forest plot for injuries of any severity is given in Figure 3 and a forest plot of serious and fatal head injury is given in Figure 4. In both figures, summary estimates were taken from Model 4. Helmet use was associated with a 51% reduction in the odds of head injury (OR = 0.49, 95% CI: 0.42–0.57), a 69% reduction in serious head injury (OR = 0.31, 95% CI: 0.25–0.37), a 33% reduction in facial injury (OR = 0.67, 95% CI: 0.56–0.81) and a 65%

Table 2. Summary of meta-analysis models

Model	AIC	I^2	LRT	df	*P*-value
(1) Baseline	573.5	85.4%			
(2) + injury type	242.6	68.1%	338.9	4	< 0.0001
(3) + random intercept	180.4	—	64.2	1	< 0.0001
(4) + random slope	145.0	—	37.4	1	< 0.0001

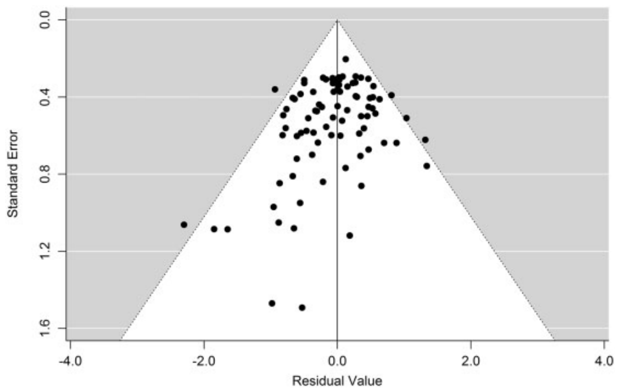

Figure 2. Funnel plot of residuals from multivariate meta-regression model.

reduction in fatal head injury (OR = 0.35, 95% CI: 0.14–0.88). The odds ratio for helmet use and neck injury was near a null effect (OR = 0.96, 95% CI: 0.74–1.25).

Discussion

This systematic review of bicycle helmet effectiveness identified 43 relevant studies of which 40 were included in a meta-analysis. This includes 24 studies not included in previous meta-analyses (see Figure 5). The effectiveness of bicycle helmets differed by injury type and, unlike a recent review, there was no evidence of publication or time trend bias. Helmet use among cyclists in a crash was associated with reduced odds of head, serious head, face and fatal head injury. In particular, the magnitude of the reduction was greater for serious injury (serious head, OR = 0.31; fatal head, OR = 0.35) than those for any injury severity (head, OR = 0.49; face, OR = 0.67).

Comparison with other meta-analyses

This study differs from previous reviews and meta-analyses in several ways. Due to criticisms of the Cochrane Review, minimal selection criteria were chosen similar to Attewell and colleagues; however, medically verified injuries were required to minimize the influence of bias in self-reported data. This eliminated three studies included in other reviews.[62,64,65] The search was also limited to English language publications, and Elvik included two non-English language studies–a French technical report by Amoros *et al.*[79] and a German medical insurance report.[80] Amoros and colleagues later published their work in an English language journal which has been included in this review. To assess the influence of excluded studies, the final multivariate meta-regression model was refit including the three studies with self-reported injury data and the German language study. The summary odds ratios for each injury type changed very little (see Table A1, available as Supplementary data at *IJE* online).

Table 3 contrasts the current results from those in previous meta-analyses. With regards to head injury of any severity, the current results are most similar to Elvik. The inclusion of more studies, therefore, may support Elvik's claim that estimates of helmet effectiveness have evolved over time. However, no evidence of time trend bias was found and the summary results change very little if the analysis is restricted to studies published in the past 10 years (see Table A1, available as Supplementary data at *IJE* online). Note that any visual evidence of publication bias vanishes when considering only recently published studies, which may indicate higher quality data, improved diagnostics or more acceptance of studies that do not pass the $P < 0.05$ threshold in this area.

Similar protective effects were found for serious head and facial injuries to those by Thompson *et al.* in their Cochrane Review. Elvik was highly critical of the inclusion criteria used in the Cochrane Review and suggested sensitivity analyses be performed to assess its impact on the summary measures. Since the inclusion criteria of this review were more similar to Elvik, the final model was refit only on studies that collected data prospectively, which is similar to the Cochrane Review. With the exception of studies with fatal head injury which collected data retrospectively, the summary estimates were similar to the final model (see Table A1, available as Supplementary data at *IJE* online).

The estimates of neck injuries differ substantially from both Attewell *et al.* and Elvik. Like head injuries, the association of helmet use and neck injuries has lessened in magnitude from the first included study (OR = 1.80), to Elvik's estimate from four studies (OR = 1.28) and then to the current summary measure that includes 12 studies (OR = 0.96). Fatal head injury was not included in previous meta-analyses, but the current estimate is similar to that reported by Attewell and colleagues for fatal versus non-fatal injury by helmet use.

With the exception of the summary estimate for head injury, the current results run counter to the most recent meta-analysis by Elvik. No strong evidence was found of either publication or time trend bias. There is some visual evidence of funnel plot asymmetry, but this is due to two studies with small sample sizes and therefore has little to no impact on the analysis. As a demonstration, three effect sizes were added to the right of their summary odds ratios to 'balance' the funnel plot. The summary odds ratios were nearly identical to the final model (see Table A1, available as Supplementary data at *IJE* online). Following a systematic search for studies, 24 studies not included in Elvik's meta-analysis were identified, with five published before 2011. Therefore, it is possible the previously identified biases are partly an artefact of not performing a systematic search for studies. Large, protective effects associated with helmet use were found for serious or fatal head injuries which were not included by Elvik.

Elvik also claimed that bicycle helmets offer no overall protection to the head, face or neck, from an analysis of 'new' studies that estimated a summary odds ratio from the trim-and-fill method. When Elvik's method of analysis was repeated to the 'new' studies (i.e. a no-moderator, random effects model on head, face and neck injuries using studies not included in Attewell and colleagues), little evidence was found for funnel plot asymmetry by the rank correlation test ($\tau = -0.08$, $P = 0.43$). The trim-and-fill method does add five hypothetical studies; however, the summary odds ratio changes little (OR = 0.60 versus OR = 0.64) and the statistical results are not consistent with Elvik's results (95% CI: 0.55–0.75). Note that as with the primary analysis where injury type is included as a moderator, the odds ratio for head injury differs from face ($P = 0.012$) and neck injury ($P < 0.001$) and heterogeneity is reduced compared with Elvik's approach of combining injury types ($I^2 = 88.8\%$ versus $I^2 = 74.4\%$ with injury type). This suggests that helmets affect head, face and neck injuries differentially, thereby invalidating any overall summary measure that combines these injuries.

Risk compensation

In a series of commentaries in 2001, the Cochrane Review was criticized for not accounting for risk compensation.[81] As defined by Adams and Hillman in this context, the risk compensation hypothesis posits that bicycle helmet use alters a cyclist's behaviour in a manner that offsets the protective effect of wearing a helmet in a crash. In a response, Thompson *et al.*[82] found little empirical support for the hypothesis and called for a systematic review of the published evidence around risk compensation and bicycle helmets. Since this debate, there has been very little published research on the topic and no systematic review.

With regards to this review, adjusted summary estimates are not possible without study-level data on risk compensation, irrespective of whether the hypothesis is supported by evidence. For example, Messiah *et al.*[83] used average cycling speed as a measure of risk; however, the speed of the cyclist at the time of a crash is unknown for every study included in this review.

The results from two recent, large studies do shed some light on the risk compensation hypothesis. Amoros and colleagues used multivariable logistic regression models to adjust for several factors including injury severity score for injuries below the neck as a proxy for crash severity.[10] Covariate adjustment increased the estimates of helmet protectiveness, as opposed to a decrease under the risk compensation hypothesis, for any head injury [OR = 0.78, 95% CI: 0.67–0.90; adjusted OR (aOR) = 0.69, 95% CI: 0.59–0.81] and for AIS3+ head injuries (OR = 0.41, 95% CI: 0.24–0.70; rural area, aOR = 0.07, 95% CI: 0.02–0.23; urban area, aOR = 0.34, 95% CI: 0.15–0.65). Bambach *et al.*,[2] in an analysis of head injury severity for cyclists in a motor vehicle collision using multinomial logistic regression, also adjusted for other serious injuries as well as behavioural factors such as posted speed limit, disobeying a traffic control, blood alcohol content over 5% and riding on a footpath. Compared with possible minor injury, the crude and adjusted odds ratios are nearly identical for moderate head injury (OR = 0.513 versus aOR = 0.506), serious head injury (OR = 0.330 versus aOR = 0.378) and severe head injury (OR = 0.259 versus aOR = 0.257). These results suggest that an adjustment for risk compensation is difficult due to a lack of data and such an adjustment may also be unnecessary.

Neck and diffuse axonal injury

In his meta-analysis, Elvik found that helmet use was associated with increased odds of neck injury; however, the inclusion of more studies brings those results into question. The current estimate of helmet use and neck injuries is near a null effect (OR = 0.96, 95% CI: 0.74–1.25). Additionally, the review of the literature found that neck injury is not common and usually of low severity. McDermott et al.[14] found that 3.8% (65/1710) of injured cyclists had neck injuries, with only four with severities greater than AIS1. Airaksinen *et al.*[84] reported 300 injuries from 216 cyclists, of which there were two AIS1 neck injuries and no AIS2+ neck injuries. From data found in the publication or provided by the authors, the proportion of neck injured cyclists was 2.5% (76/3004) for Rivara *et al.*,[15] 0.3% (2/682) for Sze *et al.*,[85] 6.3% (529/8373) for Amoros *et al.*,[10] 0.9% (1/110) for Dinh *et al.*[86], 3.6% (5/137) for McIntosh *et al.*,[25] 2.4% (9/374) for Webman *et al.*[87], 8.8% (22/249) for Hooten and Murad,[88] 1.2% (181/15569) for Lindsay and Brussoni,[89] 10.8% (20/186) for Zibung *et al.*[90], 0.8% (2/254) for Dinh *et al.*,[91] 0.4% (31/7678) for Gulack *et al.*,[92] 1.8% (10/567) for Kaushik

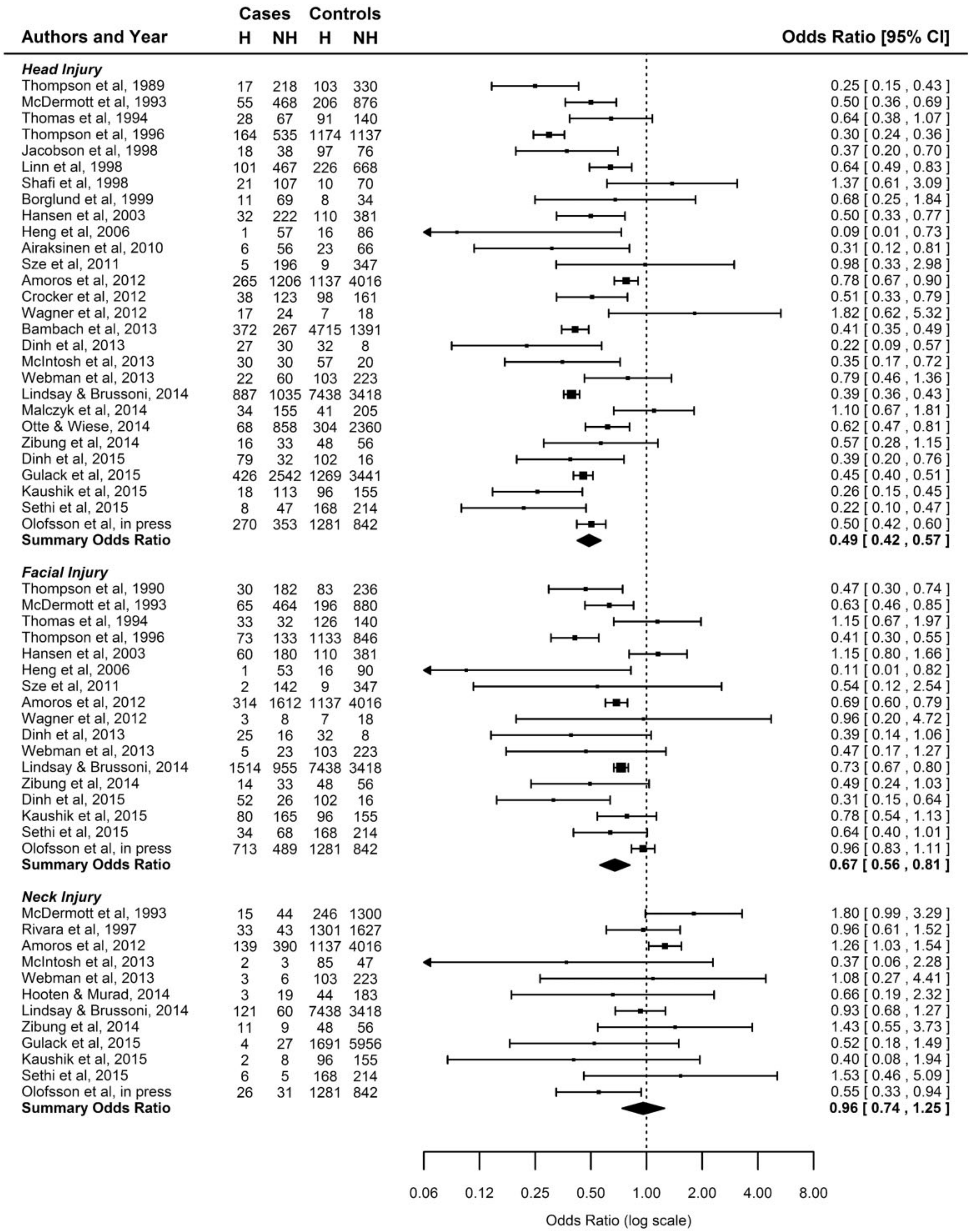

Figure 3. Forest plot of odds ratios (95% CI) of helmet use and head, face and neck injury from individual studies and multivariate meta-regression. H, helmet; NH, no helmet.

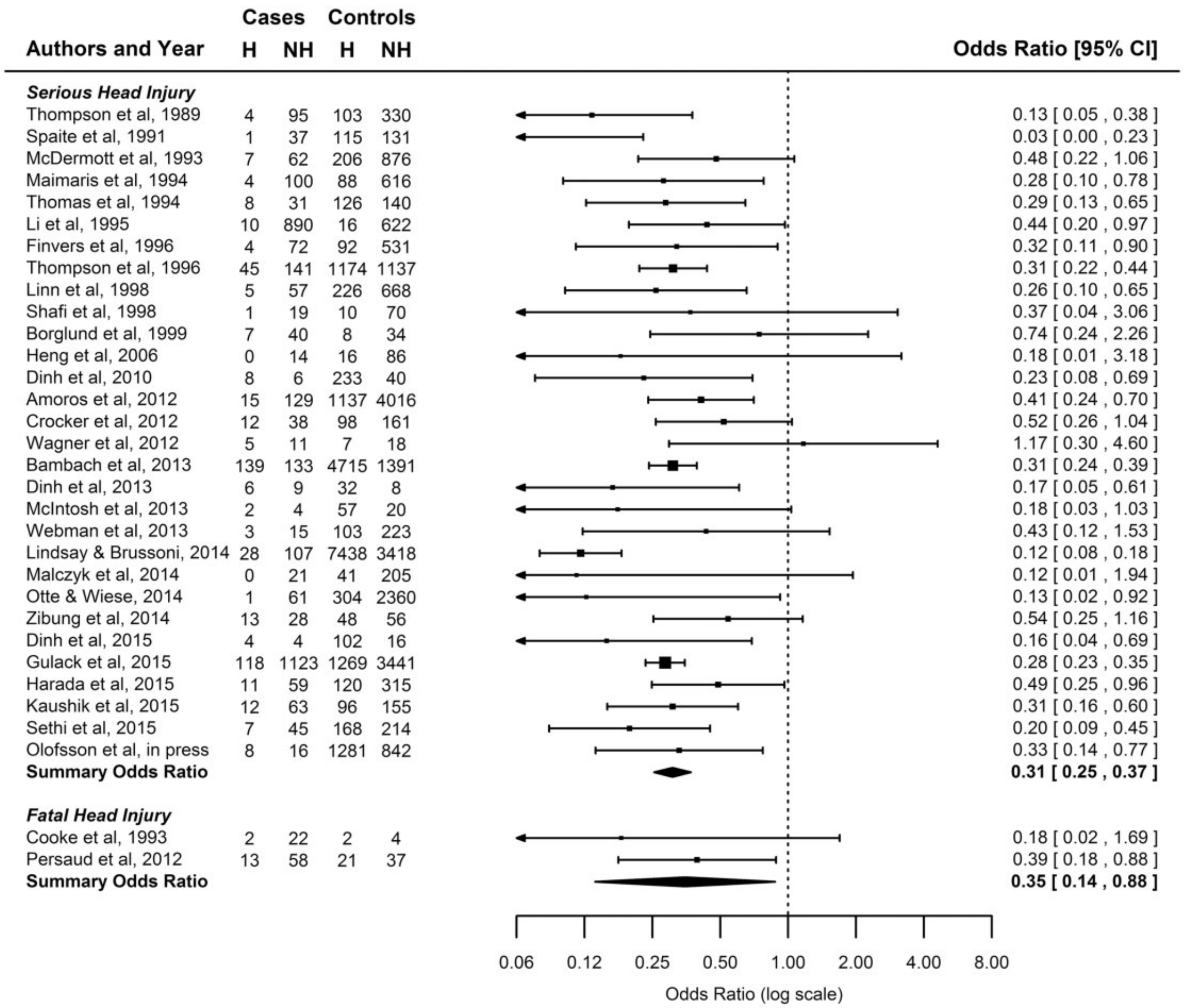

Figure 4. Forest plot of odds ratios (95% CI) of helmet use and serious and fatal head injury from individual studies and multivariate meta-regression. H, helmet; NH, no helmet.

Figure 5. Venn diagram of included studies from systematic reviews or meta-analyses of bicycle helmet effectiveness.

et al.,[93] 1.6% (11/699) for Sethi *et al.*[94] and 1.5% (57/3711) for Olofsson *et al.*[95] The proportion of those with head injuries was always much greater except for Rivara *et al.* and Hooten and Murad, who did not report head injuries. Across all studies, the proportion of cyclists with neck injuries (2.6%) was much less than of those with injuries to the head (29.0%), serious head (7.4%) or face (21.9%).

Some authors have posited that helmet use exacerbates the occurrence of diffuse axonal injury (DAI), which has prompted biomechanical research into helmet use and angular acceleration.[5] There is biomechanical evidence that rotational forces are associated with certain types of brain injuries;[96] however, there is a paucity of research on the influence of helmet use on head rotation, although recent biomechanical studies suggest a protective effect of helmets.[5,6] Like neck injuries, this review found a DAI

Table 3. Comparison of summary odds ratios (95% CI) from past systematic reviews and meta-analyses

Injury type	Thompson *et al.*[a]	Attewell *et al.*	Elvik[b]	Olivier & Creighton
Head	0.31 (0.26–0.37)	0.40 (0.29–0.55)	0.50 (0.39–0.65)	0.49 (0.42–0.57)
Serious head[c]	0.31 (0.23–0.42)	0.42 (0.26–0.67)	—	0.31 (0.25–0.37)
Face	0.64 (0.49–0.84)	0.53 (0.39–0.73)	0.79 (0.62–1.01)	0.67 (0.56–0.81)
Neck	—	1.36 (1.00–1.86)	1.28 (1.06–1.55)	0.96 (0.74–1.25)
Fatal[d]	—	0.27 (0.10–0.71)	—	0.35 (0.14–0.88)

[a]Adjusted summary odds ratios for head and serious head, crude odds ratio for any facial injury.
[b]Random effects meta-analysis adjusting for publication bias except for neck injury.
[c]Brain injury in Thompson *et al.*[17] and Attewell *et al.*[11]
[4]Fatal injury of any type for Attewell *et al.*[11]

diagnosis is rare among cyclists in a crash. There were no DAI diagnoses reported by Dinh *et al.*[86] (0/110), McIntosh *et al.*[25] (0/137) or Malczyk *et al.*[97] (0/239), whereas Javouhey *et al.*[50] reported DAI in 2.3% of cyclists (28/1238). Sethi and colleagues[94] reported DAI in 2/225 unhelmeted cyclists and 1/110 helmeted cyclists (OR = 1.02, $P = 0.99$), and Bambach *et al.*[2] identified only 0.1% (8/6745) of cyclists in a motor vehicle collision that met one criterion for DAI. There is some evidence in the motorcycle helmet literature that travel speed interacts with helmet effectiveness,[98] i.e. there is a threshold where helmet use switches from beneficial to detrimental. However, this study estimated a switch at 124 km/h which is only possible under extreme conditions on a bicycle.

Mandatory helmet legislation

The legislation of mandatory helmets for cyclists is a controversial topic, and past research on its effectiveness has been somewhat mixed. A 2008 Cochrane Review concluded that helmet legislation was beneficial,[99] whereas later studies found benefits,[89,100,101] no effect[102] or mixed results by gender.[103] Irrespective of past research, the results of this review do not support arguments against helmet legislation from an injury prevention perspective. With consideration of the difficulty in generalizing a meta-analysis of case-control studies to a population level, these results could be used as one source of evidence for the promotion of bicycle helmets for mitigating head, serious head, face and fatal head injuries without increased risk of other injuries. However, bicycle helmets are not a panacea for cycling injury, as they do not eliminate head or face injury and they do not offer protection to other body regions. Any comprehensive cycling safety strategy should consider the promotion or legislation of bicycle helmets only in concert with other injury prevention strategies.

Limitations

There are several limitations to this systematic review and meta-analysis. Several relevant studies were not included due to lack of or unreliable published data (n = 22), or the study only reported data on cases ($n = 7$) or the published report was an abstract only ($n = 4$). Whenever relevant data were missing from the published paper, study authors were contacted. In the 33 instances described above, study authors did not supply relevant information to warrant inclusion in the meta-analysis or the study authors did not respond to communication. Data were provided on cases not reported in the publication or the number of cyclists injured below the neck for 11 other studies.[2,85–87,89–91,93,95,104,105] Many of the reviewed studies were published 10 or more years ago, and this is likely the reason for the poor response rate.

There was a moderate to high amount of residual heterogeneity among effect sizes in the final model ($I^2 = 68.1\%$). This may have been influenced by a wide variety of injury definitions from study to study, although analysis of individual injury types indicates this is primarily for head injury of any severity and facial injuries ($I^2 = 84.0\%$ for head, $I^2 = 78.9\%$ for face) as there was much less heterogeneity for serious head injury ($I^2 = 42.3$) or neck injury ($I^2 = 35.7\%$). The high level of heterogeneity may also be due to differences in the cycling environment, attitudes towards cyclists by other road users or differences in bicycle helmet standards adopted by the USA (CPSC), Europe (EN 1078) and Australia/New Zealand (AS/NZS 2063). When continent is used as a moderator for helmet use and head injury of any severity, heterogeneity is reduced somewhat ($I^2 = 74.3\%$) and the summary odds ratios vary considerably (Australia, OR = 0.42; Asia, OR = 0.55; Europe, OR = 0.62; North America, OR = 0.45). However, the inclusion of continent does not improve model fit (AIC: 46.4 versus 44.5, LRT = 4.14, $P = 0.247$).

The statistical methods used assume that the log odds ratios are independent between studies, although it is possible that an injured cyclist could be included in more than one study. The influence of double counting was minimized by excluding studies whose data were a subset of another study. For example, data from the German In-Depth Accident Study (GIDAS) were used in five studies,[46,51,52,60,106] and the article with the most complete data that met inclusion criteria was included. It was not possible to choose one study for a series of studies from New South Wales, Australia.[2,25,86,107] The study by Bambach and colleagues covers a much longer period of time than the other studies; however, they limited the study population to police-reported motor vehicle collisions. The other studies included all admissions regardless of injury mechanism or whether the incident was reported to the police. To assess the influence of these potentially related studies, the analysis was repeated only including the NSW study with the most conservative odds ratios, and the results did not change appreciably (see Table A1, available as Supplementary data at *IJE* online).

If helmet use has an influence on head, face or neck injuries, cyclists with those injuries should be excluded from the control group. Poorly chosen controls could bias the statistical results. Of the 14 studies with data on cyclists injured solely below the neck, only three included these data in the published report. To investigate the influence of choice of controls, the final model was re-analysed only with studies with no head, face or neck controls. The results were similar to the analysis on the full data with the exception of fatal head injury (see Table A1, available as Supplementary data at *IJE* online). This discrepancy is due to the inclusion of only one fatal head injury study.

There were only two studies that reported fatal head injury, and the summary estimates could be greatly improved with more research using coronial data. Two studies reported no serious head injuries for helmeted cyclists, and a continuity correction of adding 0.5 to each cell was used to allow for estimation of the log odds ratio and its variance. This method is known to perform poorly in some circumstances.[108] The analysis was repeated using a random effects logistic regression model in SAS PROC GLIMMIX which does not require adjustment of the raw data. The summary odds ratios for each injury type did not change appreciably (see Table A1, available as Supplementary data at *IJE* online).

Conclusion

Helmet use is associated with odds reductions of 51% for head injury, 69% for serious head injury, 33% for face injury and 65% for fatal head injury. Injuries to the neck were rare and not associated with helmet use. These results suggest that strategies to increase the uptake of bicycle helmets should be considered along with other injury prevention strategies as part of a comprehensive cycling safety plan.

Supplementary Data

Supplementary data are available at *IJE* online.

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