Risk Factors for Bicycling Injuries in Children and Adolescents: A Systematic Review

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abstract

CONTEXT: Child and adolescent bicycling is beneficial, but injuries occur and can be severe and costly.

OBJECTIVE: To systematically review the individual and environmental factors associated with bicycling injury risk in children and adolescents.

DATA SOURCES: Fourteen electronic databases were searched.

STUDY SELECTION: Two authors independently assessed potentially relevant articles for eligibility. The inclusion criteria were as follows: bicyclists younger than 20 years old; examined individual and environmental characteristics of bicycling crashes; compared injured and uninjured bicyclists or bicyclists with different types or severity of injury; study designs with a predetermined comparison group; and published in English from January 1990 to May 2015. The exclusion criteria were outcomes related to helmet use, helmet legislation, or mountain biking, and comparisons of census-based injury rates.

DATA EXTRACTION: Data on study design, setting, population, injury definitions, injury risk factors, and results were extracted. Risk of bias was assessed by using the Newcastle-Ottawa Scales.

RESULTS: Fourteen articles were included. Lower socioeconomic status, riding on the road, riding in rural compared with urban areas, and riding on the sidewalk were associated with bicycling injury. Bicycling safety education did not protect children against future injury. Injuries related to a motor vehicle collision were more severe than other bicycling injuries.

LIMITATIONS: Study heterogeneity prevented meta-analyses. Study quality was affected by inadequate definitions of study groups and self-reported data.

CONCLUSIONS: Lower socioeconomic status and riding location were associated with bicycling injury and severity increased with motor vehicle collisions. The bicycling environment is a promising avenue for prevention.

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Ms Embree conceptualized and designed the study selection and data extraction processes and tools, coordinated study selection, assessed articles for inclusion, extracted and analyzed data, drafted the initial manuscript, and revised the manuscript; Ms Romanow conceptualized and designed the review, carried out the literature searches, and critically reviewed the manuscript; Ms Djerboua assessed articles for inclusion, extracted and analyzed data, and critically reviewed the manuscript; Ms Morgunov conceptualized and designed the review, carried out the literature searches, assessed articles for inclusion, drafted the initial

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Bicycling is an excellent form of physical activity for children and adolescents and an environmentally friendly form of transportation.[1,2] However, bicyclists constitute 2% to 8% of child road traffic-related deaths and 3% to 15% of child road traffic-related injuries worldwide.[3] In Canada, bicycling injuries are among the top 3 causes of unintentional injury hospitalizations for children ages 0 to 14.[4] In the United States, bicycling is the second most frequent sport and recreation activity, after football, leading to emergency department (ED) visits in children.[5] Child bicyclists injured in motor vehicle (MV)-collisions are twice as likely to require assistance with daily activities 6 months postinjury compared with child bicyclists injured in other ways.[6] Health care costs arising from injuries to bicyclists of all ages in Canada in 2010 were estimated at nearly $300 million.[7]

Recent US studies reveal a bicycling injury rate of 501 per 100 000 population for 5- to 14-year-olds on the basis of ED visits[5] and a hospitalization rate of 12.7 per 100 000 for 0- to 19-year-olds.[8] Younger adolescent boys (10–13 years old) have the highest bicycling injury rates, whereas older adolescent girls (14–17 years old) have the lowest.[8,9] Based on police reported crashes and hospitalizations in Australia and ED visits in the United States, adolescents have greater bicycling injury rates than children or adults.[10–12] Regardless of the data source, the proportions and rates of bicycling injuries in boys are consistently greater than girls.[8–10,13–17]

Bicycling injury risk factors have been widely studied by using all ages data,[18–25] and 2 recent systematic reviews have focused on child and adolescent injury risk factors.[26,27] These have revealed that child targeted bicycle helmet legislation is associated with decreases in mortality and head injuries after legislation[26]; however, bicycle skills training interventions for children are not effective in reducing injury risk.[27] Research examining transportation infrastructure and bicycling injury risk is on the rise, and a 2009 systematic review suggests that bike-specific infrastructure such as bike lanes and bike paths reduce bicycling injury risk while major roads, multiuse trails, sidewalks, and multilane roundabouts without a separate bike lane increase risk.[25] Because the 2009 review examined research on bicyclists of all ages, there is a research gap regarding transportation infrastructure (the bicycling environment) and bicycling injury risk in children and adolescents. We undertook this systematic review to examine the effects of individual and environmental factors on bicycling injury risk in children and adolescents. Due to the strong evidence for the protective effect of helmets and child targeted helmet legislation against head, brain, and facial injury,[21,22,26] this review does not include studies that focus solely on bicycle helmet and legislation effectiveness.

METHODS

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses checklist was followed in the execution and reporting of this systematic review.[28]

Study Eligibility

The study inclusion criteria were as follows: bicyclists younger than 20 years old; examined individual and environmental characteristics of bicycling crashes; compared injured and uninjured bicyclists or bicyclists with different types or levels of severity of injury; reported outcomes of bicycling injury events (ie, crashes, injuries, or deaths) or exposure-based injury rates; study designs with a predetermined comparison group such as randomized or nonrandomized controlled trials, cohort, case-control, case-crossover, and multiple time series; and studies published in English from January 1990 to May 2015. The exclusion criteria were as follows: bicyclists injured while riding a mountain bike or electric bike; comparisons of census-based injury rates; and letters to the editor, systematic reviews, and cross-sectional studies. Injury outcomes related to bicycle helmet and legislation effectiveness were excluded, but results related to other risk factors (including helmet fit) were retained.

Information Sources

A comprehensive literature search of 14 electronic databases (Academic Search Complete, Cumulative Index of Nursing and Allied Health Literature with Full Text, Embase, Medline, SportDiscus, Web of Science, ProQuest Dissertations and Theses, Google Scholar, HealthSTAR, Cochrane Database of Systematic Reviews, Cochrane Central Register of Controlled Trials, Scopus, ScienceDirect, and Educational Resources Information Centre) was conducted in June 2012 and updated in May 2015.

Search Strategy

We consulted a research librarian to develop individualized search strategies for each database. Searches were conducted by using combinations of the following exploded subject headings and keywords: accidents-traffic, accident prevention, wounds, injury, fatal, crash, collision, collide, bicycling, bike, cycling, cyclist, child, pediatric, youth, minor, school age, under age, and adolescent. The search was restricted to articles published in English and a pediatric filter was applied when available. Conference abstracts and gray literature were included. Table 1 presents the

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TABLE 1 Medline Search Strategy

1	Explode "Accidents-Traffic"/all subheadings
2	Explode "Accident-Prevention"/all subheadings
3	Explode "Bicycling"/all subheadings
4	Child mp or explode child
5	(Child* or children* or adolescent* or youth* or young people* or pediatric*)mp
6	(Bicycl* or cycle or cycling or cyclist*)mp
7	(Injur* or fatal* or accident* or crash* or prevent* or collide* or collision*)mp
8	1 or 2 or 7
9	3 or 6
10	4 or 5
11	8 and 9 and 10
12	Limit 11 to (English language and yr="1990-current")
13	Limit 11 to (English language and yr="1990-current" and "all child (0 to 18 years)")

Medline search strategy; those for the other databases are similar.

Study Selection

The references were imported into Synthesis, a custom-written Java-based literature review application for improved bibliographical management.[29,30] Two authors independently screened the article titles and abstracts in Synthesis and entered ratings of include or exclude. Next, the potentially relevant articles (and any disagreed upon at the screening stage) were retrieved, and 2 authors independently assessed the full-text to determine which met eligibility criteria. Disagreements between the 2 authors were resolved through discussion that involved a third author if required.

Data Extraction

One author extracted information (study design, setting, population, injury definitions, injury risk factors, and results) from the articles and entered it into a table. A second author checked the data extraction for completeness and accuracy. Adjusted results were reported when possible, and only results for children and adolescents were reported when the study samples contained all ages.

Risk of Bias in Individual Studies

Two authors independently assessed the risk of bias of the included studies by using the Newcastle-Ottawa Scales (NOS) for nonrandomized studies.[31] The NOS Cohort uses 8 criteria to evaluate selection bias, cohort comparability, and outcome assessment and has been used in another injury-related review.[32] The NOS Case Control uses 8 criteria to evaluate selection bias, comparability of groups, and exposure ascertainment. We modified the NOS Case Control to better serve the needs of this review (Supplemental Table 5). Specifically, we added descriptive information from the NOS coding manual to clarify the response choices for several criteria and removed the distinction between community and hospital controls in selection criterion 3, which assessed whether controls were derived from the same source population as the cases.[33] In injury research, controls recruited from hospitals or EDs can fulfill that criterion. We also simplified the comparability criterion to assess whether the researchers attempted to address confounding (yes/no) rather than assessing the number and type of control factors used. In sum, the changes to the NOS Case Control reduced the maximum possible score from 9 to 8 points. The 2 authors compared their ratings and reported their level of agreement on each criterion. They discussed any differences and provided a consensus rating.

Data Synthesis

Due to the heterogeneity of the study designs, risk factors, and injury definitions among the reviewed studies, no synthesis of results or meta-analyses were attempted. Instead, the authors summarized the results in a table and performed a descriptive analysis.

RESULTS

The database searches identified 4950 article titles and, after removing duplicates, 4088 titles and abstracts were screened. The full-text of 568 articles were assessed for eligibility and 14 studies met the inclusion criteria.[18,23,34–45] Figure 1 depicts the flow of study identification and assessment and lists the reasons studies were excluded.

Description of Included Studies

The included studies are summarized in Table 2. Four studies were conducted in Australia,[34–36,41] 4 in the United States,[23,39,42,44] 3 in Canada,[18,37,40] 1 in Norway,[38] and 2 in Taiwan.[43,45] Study designs included 9 case-control[18,23,35–37,42–45] and 1 retrospective cohort.[38] Four did not self-identify as case-control studies, but conducted predetermined comparisons of severely and less severely injured bicyclists[34,41] or comparisons of bicyclists with head injuries and those with other injuries.[39,40] The majority were conducted in a pediatric population, and 3 studies[18,23,34] included all age groups while providing subgroup data for children and adolescents. Five studies were published within the last 10 years,[18,34,37,41,45] 8 were published over 10 up to and including 20 years ago,[23,36,38,40,42–44] and 2 over 20 years ago.[35,39] The sources of injury data were ED records,[18,35–37,42,44] trauma registries,[39,45] administrative databases,[40,41] self-reported survey data,[38,43] coroners' records,[23] and police reported crashes.[34] Bicycling injury comparisons included the following: injured with noninjured,[35,36,38,43] severely injured with less severely injured,[34,37,41]

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bicycling injuries with nonbicycling injuries,[44] head injuries with other injuries,[39,40,42] severe (Glasgow Coma Scale [GCS] ≤8) head injuries with mild to moderate head injuries,[45] fatal with nonfatal injuries,[23] and injured in an MV collision with injured in other ways.[18] Authors of the included studies defined severe injuries as police reported deaths or injuries requiring transport to hospital,[34] injuries requiring hospital admission,[37] or injuries with an International Classification of Disease Injury Severity Score (ICISS) of ≤0.941.[41]

Risk of Bias in the Included Studies

Two authors used a modified NOS Case Control (Supplemental Table 5) or the NOS Cohort[31] to rate risk of bias. The consensus criterion scores for the case-control studies are presented in Table 3. The total scores for the 13 case-control studies ranged from 3 to 6 out of 8. Eight of the case-control studies received a total score of 5 or greater,[35–37,39–41,44] and we considered them to be higher quality studies because they had adequate case definitions, controls derived from the same population as the cases (control selection), and attempted to address confounding through design or analysis. The remaining case-control studies scored less than 5 [18,23,34,42,43,45] and we considered them to be lower quality studies because they received inconsistent ratings across these domains. Overall, many of the case-control studies met the criteria for case definition (85%), control selection (92%), comparability (69%), exposure ascertainment (54%) and same method of exposure ascertainment for cases and controls (100%). The cohort study,[38] scoring 7 out of 9, did not receive full points because exposure ascertainment and outcome assessment were self-reported (Table 4).

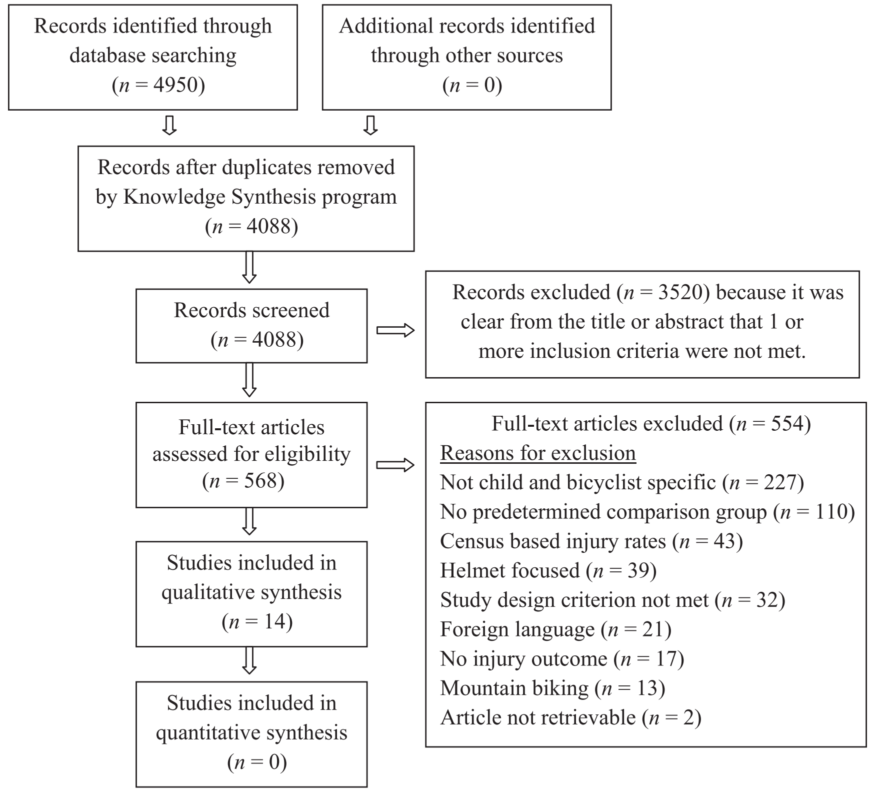

FIGURE 1
Study selection flow diagram.

Bicycling Injury Risk Factors

The included studies examined 45 different risk factors. The most commonly reported were age,[18,23,34–37,39,40,45] sex,[35–40,45] socioeconomic status (SES),[35–37,40] and collision involvement.[37,39,41,45] Other individual risk factors included those related to bicycling equipment (*n* = 5 factors; eg, use of reflective articles/lights, helmet width), bicyclist behavior (*n* = 5 factors; eg, riding with companions, bicycling speed), bicycling exposure (*n* = 5 factors; eg, distance bicycled per week, amount of time bicycled per week), and bicycling purpose (*n* = 3 factors, proportion of time spent in play, stunt riding). Twelve unique factors related to the bicycling environment were identified (ie, riding location, urban/rural, traffic volume, vehicle speed, speed limit, obstacles, riding surface, weather, light conditions, daytime, weekday peak time, and weekend).

Individual Factors

Age

Within the child and adolescent age groupings, age was not associated with presenting to an ED with a bicycling injury,[35,36] police reported injury resulting in death or requiring transport to hospital,[34] injury requiring hospital admission,[37] or admission to a trauma center or hospital for a head injury[39,40] among the majority of studies that controlled for potential confounders. Studies that did not control for potential confounders showed inconsistent results.[18,23,45]

Sex

Among the higher quality studies, sex was not associated with presenting to an ED with a bicycling injury,[35,36] admission to a trauma center or hospital for a head injury,[39,40] or time to first bicycle riding injury.[38] However, Hagel et al[37] found that boys had a twofold greater risk of injury requiring hospital admission

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TABLE 2 Summary of Included Studies

Study: First Author, Year, Design	Setting: Location, Time Period, Data Source	Participants: Age, Sample Size	Injury Outcome	Risk Factor	Results: OR, HR, Wilcoxon Rank Sum, χ^2
Boufous, et al 2012,[34] case-control	Australia; 2004–2008; Police reports of cycling related crashes on public roads	All ages, $N = 6432$	Case: severe injury (police reported death or injury requiring hospital transport); Control: cyclist in a traffic crash without severe injury	Age	Risk of severe injury (OR)[a] Age: 0–9 y: 1.0 (Ref); 10–19: 1.11 (95% CI: 0.75–1.63); Adjusted for helmet use, light condition, crash type, speed limit, urban/rural location and road curvature
Carlin et al 1995,[35] population-based case-control	Australia; April 1993–April 1994; ED records, interviews with child and parent	5–14 y, Cases: 109 Controls: 118	Case: injured cyclist presenting to ED; Control: cyclist found by telephoning random numbers	Age, sex, income, parent's education, Daniel's scale of occupational prestige (skill level), total distance (kilometer per week), weekly distance by street type, total cycling time (minutes per week), proportion of riding time spent in play versus purposeful travel	Risk of injury (OR)[b] Age: 5–8 y: 1.0 (Ref); 9–11: 1.33 (95% CI: 0.71–2.5); 12–14: 1.02 (95% CI: 0.52–2.0) Sex: Boy: 1.35 (95% CI: 0.77–2.4); Girl: 1.0 (Ref); Income: <\$20 000: 4.3 (95% CI: 1.8–10.4); \$20 000–\$30 000: 1.9 (95% CI: 0.82–4.2); \$30 000–\$40 000: 1.7 (95% CI: 0.76–3.6); >\$40 000: 1.0 (Ref); Parent's education: Primary: 1.8 (95% CI: 0.77–4.3); Secondary/tech: 1.6 (95% CI: 0.8–3.2); Tertiary: 1.0 (Ref); Occupational prestige: first tertile: 1.0 (Ref); second tertile: 1.5 (95% CI: 0.77–2.9); third tertile: 1.1 (95% CI: 0.55–2.1) Weekly distance: 0 km (play): 1.0 (Ref); 0–5 km: 0.56 (95% CI: 0.29–1.1); >5 km: 1.1 (95% CI: 0.57–2.2) Weekly distance on busy streets: 0 km: 1.0 (Ref); 0–5 km: 1.7 (95% CI: 0.72–3.8); >5 km: 1.5 (95% CI: 0.43–4.9); Weekly distance on local streets: 0 km: 1.0 (Ref); 0–5 km: 0.76 (95% CI: 0.41–1.4); >5 km: 1.1 (95% CI: 0.51–2.2); Weekly distance on sidewalks: 0 km: 1.0 (Ref); 0–5 km: 0.83 (95% CI: 0.48–1.5); >5 km: 3.1 (95% CI: 1.1–8.5) Weekly cycling time: 0–60 min: 1.0 (Ref); 61–180: 1.1 (95% CI: 0.58–2.1); >180: 2.2 (95% CI: 1.1–4.2) Time spent in play: none: 1.0 (Ref); 1 ≤50% of time: 2.5 (95% CI: 0.99–6.3); 50%–99%: 2.1 (95% CI: 1.0–4.3); 100%: 2.0 (95% CI: 0.97–4.1)
Carlin, et al 1998,[36] population-based case-control	Australia; April 1993–January 1996; ED records, interviews with child and parent	9–14 y, Cases: 148 Controls: 130	Case: injured cyclist presenting to ED; Control: cyclist found by telephoning random numbers	Age, sex, income, parent's education (81% mother), occupational prestige (1 highly skilled to 7 unskilled workers), total time bicycled per week, total distance bicycled per week, total distance on sidewalks per week, participated in school based bicycle education (parent reported)	Risk of injury (OR) Bicycle education[a]: Yes: 1.57 (95% CI: 0.91–2.71); No: 1.0 (Ref); Adjusted for age, sex, income Age: 9–11: 1.0 (Ref); 12–14: 1.1 (95% CI: 0.66–1.7) Sex: Boy: 1.6 (95% CI: 0.94–2.8); Girl: 1.0 (Ref) Income: <\$20 000: 3.2 (95% CI: 1.5–6.6); \$20–\$30 000: 1.6 (95% CI: 0.8–3.1); \$30–\$40 000: 1.3 (95% CI: 0.7–2.6); >\$40 000: 1.0 (Ref) Parent's education: Primary: 3.3 (95% CI: 1.5–7.4); Secondary: 3.3 (95% CI: 1.7–6.4); Tertiary: 1.0 (Ref) Occupational prestige: High 1–3.9: 1.0 (Ref); Moderate 4–4.9: 2.0 (95% CI: 1.1–3.7); Low 5–7: 1.9 (95% CI: 1.0–3.5); Weekly cycling time: 0–60 min: 1.0 (Ref); 61–180: 0.93 (95% CI: 0.54–1.6); >180: 1.4 (95% CI: 0.74–2.5); Distance per week: 0–4 km: 1.0 (Ref); 4–12: 1.3 (95% CI: 0.69–2.4); >12: 1.1 (95% CI: 0.59–2.1); Distance on sidewalks per week: 0–2 km: 1.0 (Ref); 3–5: 1.3 (95% CI: 0.63–2.7); >5: 2.0 (95% CI: 0.95–4.0)

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TABLE 2 Continued

Study: First Author, Year, Design	Setting: Location, Time Period, Data Source	Participants: Age, Sample Size	Injury Outcome	Risk Factor	Results: OR, HR, Wilcoxon Rank Sum, χ^2
Hagel et al 2014,[18] case control	Canada; May 2008–October 2010; structured interview, ED records	All ages; n = 2403; cases = 278	Case: bicyclist injured in MV collision and seen at a study ED* Control: bicyclist with injury not related to MV collision and seen at a study ED	Age	Risk of injury (OR) Age: <13: 1.0 (Ref); 13–17: 2.68 (95% CI: 1.74–4.13)
Hagel et al 2015,[37] case control	Canada; May 2008 October 2010; structured interview, ED records	<18 y; n = 1470; cases = 119	Case: severe injury (bicyclist hospitalized after an ED visit); Control: nonsevere injury (bicyclist seen and discharged from ED)	Age, sex, collision with moving MV, use of reflective materials or lights, bicycling frequency, BMI category, parental education level, self-reported bicycling speed, medical care received for a previous bicycling injury, bicyclist reported location speed limit, pavement, light conditions, weather conditions, weekday peak time, bicycling with companions, utilitarian bicycling	Risk of severe injury (OR)[c] Age: ≤5: 1.0 (Ref); 6–12: 1.16 (95% CI: 0.58–2.31); 13–17: 0.82 (95% CI: 0.5–1.33) Sex: Girl: 1.0 (Ref); Boy: 1.96 (95% CI: 1.15–3.33) Collision with moving MV: Yes: 4.17 (95% CI: 2.11–8.24); No: 1.0 (Ref) Parental education: No postsecondary: 1.0 (Ref); Postsecondary: 0.67 (95% CI: 0.41–1.09) BMI: Underweight: 0.94 (95% CI: 0.58–1.53); Normal weight: 1.0 (Ref); Overweight: 0.85 (95% CI: 0.38–1.92); Obese: 0.55 (95% CI: 0.13–2.35) Medical care for before bicycling injury: No previous injury: 1.0 (Ref); No medical care: 1.4 (95% CI: 0.86–2.27); sought medical care: 0.81 (95% CI: 0.36–1.82) Use of reflective materials/lights: No: 1.0 (Ref); Yes: 1.67 (95% CI: 0.86–3.27) Bicycling frequency: Once/week: 1.0 (Ref); Once/month: 1.31 (95% CI: 0.56–3.06); Once/year: 0.48 (95% CI: 0.11–2.16) Self-reported bicycling speed: ≤24 km/h: 1.0 (Ref); >24 km/h: 1.95 (95% CI: 0.82–4.62) Bicyclist reported location speed limit: ≤30 km/h: 1.0 (Ref); >30 km/h: 1.01 (95% CI: 0.44–2.3); No speed limit: 0.71 (95% CI: 0.33–1.52) Pavement: Paved: 0.51 (95% CI: 0.32–0.83); Other surface: 1.0 (Ref) Light conditions: Daylight: 1.0 (Ref); Dawn/dusk: 1.24 (95% CI: 0.5–3.06). Dark: 1.14 (95% CI: 0.32–4.11) Weather: No adverse weather: 1.0 (Ref); Adverse weather: 1.01 (95% CI: 0.34–2.99) Weekday peak time: No: 1.0 (Ref); Yes: 1.03 (95% CI: 0.62–1.72) Bicycling with companions: Alone: 1.0 (Ref); With adults: 1.17 (95% CI: 0.68–2.01); With kids only: 0.89 (95% CI: 0.55–1.45) Utilitarian bicycling: All other reasons: 1.0 (Ref); Bicycling to school, work, or shopping: 0.49 (95% CI: 0.22–1.06)
Hansen et al 2005,[38] retrospective cohort	Norway; No time period; Questionnaire, registry of inhabitants	4–15 y, N = 1200 (100 of each age drawn randomly from registry)	Any bicycle-related injury in first 12 mo of riding	Age began cycling, sex, cycling time per week (hours)	Time to first injury in first 12 mo of riding (HR)[a] Age: 3–5 y: 1.0 (Ref); 6–7 y: 0.78 (95% CI: 0.62–0.99); Adjusted for cycling time, sex Sex: 0.94 (95% CI: 0.62–1.41); Adjusted for cycling time, age began cycling Cycling time per week: <1 h: 1.0 (Ref); 1–3 h: 1.96 (95% CI: 0.92–4.19); >3 h: 2.75 (95% CI: 1.29–5.87); Adjusted for age began cycling, sex

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TABLE 2 Continued

Study: First Author, Year, Design	Setting: Location, Time Period, Data Source	Participants: Age, Sample Size	Injury Outcome	Risk Factor	Results: OR, HR, Wilcoxon Rank Sum, χ^2
Li et al 1995,[39] case-control	United States; 1989–1992; National Pediatric Trauma Registry	0–14 y, $N = 2333$	Case: HI; Control: other injury	Age, sex, preexisting mental disorder, collision with object, location	Risk of HI (OR)[a] Age: 0–4: 1.0 (Ref); 5–9: 0.91 (95% CI: 0.62–1.32); 10–14: 1.11 (95% CI: 0.76–1.62); Adjusted for sex, mental disorder, helmet, collision, location Sex: Girl: 1.0 (Ref); Boy: 0.93 (95% CI: 0.77–1.14); Adjusted age, mental disorder, helmet, collision, location Mental disorder: Yes: 2.37 (95% CI: 1.32–4.26); No: 1.0 (Ref); Adjusted for age, sex, helmet, collision, location Collision with object: Other: 1.0 (Ref); MV: 0.95 (95% CI: 0.79–1.14); Bike: 1.45 (95% CI: 0.72–2.92); Adjusted for age, sex, mental disorder, helmet, location; Location: Residential area: 1.0 (Ref); Road: 1.75 (95% CI: 1.3–2.35); Other (eg, playground, park, sport field): 1.51 (95% CI: 1.05–2.2); Adjusted for age, sex, mental disorder, helmet, collision
Macpherson et al 2004,[40] case-control	Canada; 1994–1998; Hospitalization data from Canadian Institute for Health Information (CIHI)	5–19 y, $N = 9367$	Case: HI (injury to the head, face, and brain); Control: injury to other body parts	Age, sex, SES, riding in urban or rural area (population density was used to classify areas into 4 groups)	Risk of HI (OR)[a] Riding area: Urban: 1.0 (Ref); Mixed urban: 1.31 (95% CI: 1.17–1.48); Mixed rural: 1.31 (95% CI: 1.16–1.47); Rural: 1.22 (95% CI: 1.09–1.36); Adjusted for bicycle helmet legislation in home province, MV involvement. Age, sex, and SES were not associated with odds of HI in the statistical model.
Mitchell et al 2015,[41] case-control	Australia; 2001–2011; CrashLink (police-reported) data, hospital admissions records	≤16 y, $N = 612$	Injuries were classified using the International Classification of Disease ICISS Case 1: serious injury (ICISS ≤0.941); Case 2: moderate injury (ICISS between 0.941 and 0.99); Control: minor injury (ICISS ≥0.99)	Time of crash, single cyclist crash,[d] daytime	Risk of Serious Injury (OR)[a] Weekend: Yes: 1.84 (95% CI: 1.06–3.21); No: 1.0 (Ref) Adjusted for single vehicle crash, daytime Single cyclist crash: yes: 0.98 (95% CI: 0.41–2.32); no: 1.0 (Ref); adjusted for weekend, daytime Daytime: yes: 0.71 (95% CI: 0.39–1.31); no: 1.0 (Ref); adjusted for weekend, single vehicle crash Risk of Moderate Injury (OR)[a] Weekend: yes: 1.03 (95% CI: 0.62–1.73); no: 1.0 (Ref); adjusted for single vehicle crash, daytime Single cyclist crash: yes: 0.39 (95% CI: 0.17–0.94); no: 1.0 (Ref); adjusted for weekend, daytime Daytime: yes: 1.38 (95% CI: 0.78–2.46); no: 1.0 (Ref) Adjusted for weekend, single vehicle crash
Rivara, et al 1997,[23] case-control	United States; 1992–1994 Questionnaire, ED and coroners' records	All ages, $N = 3343$	Case: fatal injury; Control: nonfatal injury	Age	Risk of fatal injury (OR) Age: 6–12: 1.0 (Ref); 13–19: 1.1 (95% CI: 0.2–5.0)
Rivara, et al 1999,[42] case-control	United States; Questionnaires, ED records, physical measurements	2–14 y, $N = 126$ helmeted cyclists	Case: HI Control: other injury	Helmet width of ≥2 cm larger than head width	Risk of HI (OR) Helmet width: Boys: ≥2 cm: 15.6 (95% CI: 2.5–162.0); <2 cm: 1.0 (Ref). Girls: ≥2 cm: 1.1 (95% CI: 0.1–8.3); <2 cm: 1.0 (Ref)

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TABLE 2 Continued

Study: First Author, Year, Design	Setting: Location, Time Period, Data Source	Participants: Age, Sample Size	Injury Outcome	Risk Factor	Results: OR, HR, Wilcoxon Rank Sum, χ^2
See and Lo 1997,[43] matched case-control	Taiwan; Sep 1993–Jun 1995; Interviews, questionnaires, environmental audits	12–15 y, 197 cases matched with controls on sex, school grade	Case: bicycling injury in previous 12 mo; Control: riding bicycle in previous 12 mo with no accidents	Traffic volume, vehicle speed, obstacles	Traffic volume: More vehicles passed through case versus control sites (667 vs 585.6 per hour, Wilcoxon rank sum $P = .049$) Vehicle speed: No difference in speed was found between case and control sites for any type of vehicle Obstacles: More illegally parked vehicles (89% vs 80%, $P = .01$); more vendors (67% vs 55%, $P = .02$) at case versus control sites. No difference in rubbish or road construction
Senturia et al 1997,[44] matched case-control	United States; Jun–Jul 1995; ED records, telephone interviews	7–18 y, Cases: 47; Controls: 42; Matched on age, sex, home location	Case: injured riding a bicycle and presented to an ED; Control: child seen same day at ED for nonbicycle injury but who does ride a bicycle	Riding speed, riding location, distance from home, style of bicycle, riding companion, purpose of ride, stunt riding	Risk of a bicycle riding injury (OR)[a] Riding speed: Slow: 10.3 (95% CI: 1.6–66.8); Normal: 1.0 (Ref); Fast: 3.2 (95% CI: 0.9–11.8). Adjusted for location, distance from home, style, companion, purpose, stunting Location: Sidewalk only: 6.1 (95% CI: 1.8–20.5); Sometimes/always street: 1.0 (Ref). Adjusted for speed, distance from home, style, companion, purpose, stunting Distance from home: >3/4 mile: 3.7 (95% CI: 1.1–12.5); ≤3/4 mile: 1.0 (Ref). Adjusted for speed, location, style, companion, purpose, stunting Style of bicycle: Standard: 1.0 (Ref); Motocross/BMX: 2.4 (95% CI: 0.07–8.4); Adjusted for speed, location, distance from home, companion, purpose, stunting Riding companion: Adults: 1.0 (Ref); Alone: 0.44 (95% CI: 0.1–1.0); Children/no adults: 0.91 (95% CI: 0.1–1.8); Adjusted for speed, location, distance from home, style, purpose, stunting Purpose of ride: Travel: 1.0 (Ref); Play: 4.0 (95% CI: 0.3–47.3); Adjusted for speed, location, distance from home, style, companion, stunting Stunt riding: Yes: 1.0 (Ref); No: 2.6 (95% CI: 0.5–10.5); Adjusted for speed, location, distance from home, style, companion, purpose
Wang et al 2009,[45] case-control	Taiwan; Jan 2001–Dec 2002; Trauma Data Registry, telephone interviews	0–18 y, $N = 324$, Cases: 90	Case: severe HI (GCS ≤8); Control: mild-moderate HI (GCS ≥9)	Sex, age, bicycle with reflectors, bicycle with bells, bicyclist carrying goods, bicycling center of gravity while carrying goods, collision with others, bicycle machinery, cause of accident	Proportion of severe HI (χ^2) Sex: Boys: 34.1%; Girls: 23.4%, $P = .048$ Age: 5–9 y: 65.2%; 10–14 y: 6.4%, $P = .04$ Bicycle reflectors: Yes: 5.7%; No: 69%, $P = .004$ Bicycle bell: Yes: 29.1%; No: 27.5%, $P = .75$ Carrying goods: Yes: 90.3%; No: 9.9%, $P < .001$ Centre of gravity: toward sidewalk: 7.6%, toward road: 73.0%, $P = .035$ Collision: large vehicle: 76.9%; pedestrian: 3.6%, $P = .04$ Bicycle machinery: lost control: 69%; tripped by roller chain: 1.9%, $P = .02$ Cause of accident: greater bicyclist speed: 44.3%; inattention/distraction: 6.4%, $P = .03$

HI, head injury; HR, hazard ratio.

[a] Analysis adjusted for listed covariates.

[b] Although the authors reported crude ORs, they wrote: "there was little change (generally <10%) in any of the estimated ORs for either the exposure or sociodemographic variables when adjusted for each other in multiple logistic regression models."

[c] Multiple imputation analysis that adjusted for helmet use and all of the other variables listed in the table.

[d] We communicated with the authors of Mitchell et al 2015[41] to clarify that the variable "single vehicle crash" in tables 3 and 5 of their manuscript referred to "single cyclist crash."

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TABLE 3 Risk of Bias Ratings of Case-Control Studies and Proportion of Studies Meeting Each NOS Criterion

Case-Control Studies	Selection (Maximum 4 Points)				Comparability	Outcome (Maximum 3 Points)			
First Author, Year	Case Definition	Case Represent	Control Selection	Control Definition	Comparability	Exposure Ascertainment	Same Method	Nonresponse	Total (8)
Boufous et al 2012[34]	0	0	1	0	1	1	1	0	4
Carlin et al 1995[35]	1	1	1	0	0	0	1	1	5
Carlin et al 1998[36]	1	0	1	0	1	0	1	1	5
Hagel et al 2014[18]	1	0	1	0	0	1	1	0	4
Hagel et al 2015[37]	1	1	1	0	1	0	1	0	5
Li et al 1995[39]	1	1	1	0	1	1	1	0	6
Macpherson et al 2004[40]	1	1	1	0	1	1	1	0	6
Mitchell et al 2015[41]	1	0	1	0	1	1	1	0	5
Rivara et al 1997[23]	1	1	1	0	0	0	1	0	4
Rivara et al 1999[42]	1	0	0	0	0	1	1	0	3
See and Lo 1997[43]	0	0	1	1	1	1	1	0	5
Senturia et al 1997[44]	1	0	1	0	1	0	1	1	5
Wang et al 2009[45]	1	1	1	0	0	0	1	0	4
Proportion	11/13	6/13	12/13	1/13	9/13	7/13	13/13	3/13	
Percent	0.85	0.46	0.92	0.08	0.69	0.54	1.00	0.23	

than girls, adjusting for the 16 other variables listed in Table 2.

SES and Personal Health Status

Parental SES, determined by self-reported annual income or census income data, self-reported educational attainment, and occupational prestige (skill level), was examined in several high quality studies with inconsistent results. Specifically, children of parents in the lowest of 4 income groups had a higher risk of presenting to an ED with a bicycling injury than children of parents in the highest income group[35,36]; however, a proxy measure of parental income on the basis of census data was not associated with hospitalization for a head injury.[40] Children of parents with primary or secondary education had a higher risk of presenting to an ED with a bicycling injury than children of parents with postsecondary education,[36,37] but parental education was not associated with bicycling injury requiring hospital admission.[37] Children of parents in low to moderately skilled occupations had a higher risk of presenting to an ED with a bicycling injury than the children of parents in highly skilled occupations.[36] Two studies examined health-related variables: BMI was not associated with risk of bicycling injury requiring hospital admission[37]; however, presence of a preexisting mental disorder was associated with admission to a trauma center for a bicycling-related head injury.[39]

Bicycling Equipment

In 2 higher quality studies, the use of reflective materials or lights was not associated with injury requiring hospital admission,[37] and bicycle style or type was not associated with presenting to an ED with a bicycling injury.[44] However, the 2 other studies that examined equipment-related variables received lower quality scores.[42,45]

Bicyclist Behavior

Self-reported bicycling speed was addressed in 2 higher quality studies with differing results. Bicycling speed was not associated with injury requiring hospital admission[37]; however, bicycling at a slow compared with normal speed (odds ratio [OR] of 10.3; 95% confidence interval [CI]: 1.6–66.8) was associated with presenting to an ED with an injury.[44] There was no association between bicycling with companions versus bicycling alone and injury risk.[37,44] The 3 other bicyclist behavior variables were identified in single studies. Carlin et al[36] evaluated a school-based bicycle safety education program and found that participating in the program did not protect children against future injury. Wang et al[45] studied child bicyclists in Taiwan and found that carrying goods on the bicycle and carrying the goods positioned toward the road were associated with severe head injury.

Bicycling Exposure

Bicycling exposure was examined in several high quality studies. Children who began bicycling at ages 4 to 5 were injured earlier in their first year of bicycling compared with those who started bicycling at ages 6 to 7, regardless of sex or number of hours spent bicycling in 1 week.[38] Bicycling a longer distance (ie, >1.2 km from home) in 1 trip[44] was associated with greater injury risk, but total distance bicycled in a week was not.[35,36] Bicycling for more than 3 hours per week was related to a shorter time to a child's first bicycling injury[38] and, in the preliminary analysis of 1 study, a greater injury risk (Carlin et al[35]); however, final study results revealed no association.[36] Bicycling frequency, defined as bicycling once per week, month, or year, was not associated with risk of an injury requiring hospital admission.[37] Only 3 studies

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TABLE 4 Risk of Bias Ratings of Cohort Studies

Cohort Studies, First Author, Year	Representativeness of Exposed Cohort	Selection of Nonexposed Cohort	Exposure Ascertainment	Outcome Not Present at Start	Comparability	Outcome Assessment	Follow-up Length	Follow-up Adequacy	Total (9)
Hansen et al 2005[38]	1	1	0	1	2	0	1	1	7

adjusted for bicycling exposure in their analyses.[37,38,44]

Bicycling Purpose

Bicycling purpose was examined in several high quality studies. Two of the variables revealed interesting trends, but the effect estimates were not statistically significant. Utilitarian bicycling, defined as bicycling to school, work, or shopping, compared with bicycling for other reasons, suggested an association with lower risk of injury requiring hospitalization,[37] and spending 50% or more riding time in play compared with none suggested a greater injury risk.[35] Stunt riding was not associated with injury.[44]

Environmental Factors

Collision Involvement

Two high quality studies demonstrated that colliding with an MV is a risk factor for injury. Specifically, risk of an injury requiring hospital admission was 4.2-fold greater in bicyclists who collided with a moving MV compared with bicyclists injured in other ways,[37] and risk of a moderately serious injury (0.941 < ICISS < 0.99) was 61% lower for bicyclists in a single bicyclist crash compared with being in a road traffic collision.[41] Among bicyclists that were admitted to a trauma center, head injury risk was not associated with the variable "collided with an object" (defined as MV, another bicyclist, or injured in other ways), after adjusting for location of injury, age, sex, mental disorder, and helmet use.[39]

Bicycling Environment

Many of the higher quality studies identified environmental factors that were associated with bicycling injury risk. The risk of admission to a hospital or trauma center for a head injury was greater in rural compared with urban areas[40] and for children bicycling on the road or in public spaces (playgrounds, parks, or sports fields) compared with those bicycling in a residential area (all private places of residence including yard, garden, driveway, and garage).[39] Bicycling exclusively or more than 5 km per week on the sidewalk compared with riding sometimes or always in the street was associated with presenting to an ED with a bicycling injury.[35,44] Riding on pavement compared with other surfaces (eg, grass) was protective against injury requiring hospital admission, adjusting for collision with a moving MV.[37] Riding in daylight[37] or daytime,[41] adverse weather conditions,[37] and bicyclist-reported location speed limit[37] were not associated with injury requiring hospital admission[37] or serious (ICISS ≤0.941) injury.[41] Riding on the weekend compared with riding on weekdays was associated with serious (ICISS ≤0.941) injury.[41] In another study, riding during weekday MV rush times (compared with weekends and non-MV rush times) was not associated with injury requiring hospital admission.[37] A matched case-control study used a unique method that compared the case location (where a child bicyclist was injured) with a control location selected from a route the control subject would have taken if traveling to a similar destination as the case subject.[43] Case locations were found to have higher MV traffic volumes and more obstacles (eg, illegally parked vehicles) than control locations, but there was no difference in vehicle speed between case and control locations.[43]

DISCUSSION

Individual Risk Factors

Age, sex, and SES were the most frequently reported risk factors. The majority of studies that examined age as a risk factor revealed no association with injury. Among the higher quality studies, sex was not associated with bicycling injury risk, except in a Canadian study that revealed that among injured bicyclists who

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presented to an ED, boys had a twofold greater risk of severe injury than girls. Various measures of parental SES were shown to be associated with bicycling injury risk in children. Children of parents with low compared with high SES (measured by income, education level, and occupation skill level) had a higher risk of presenting to an ED with a bicycling injury.

The finding that low parental SES was associated with increased risk of presenting to an ED with a bicycling injury is not surprising considering the large body of evidence revealing a social gradient in health status[46] and injury risk.[47] Children from lower SES families may be more likely to live in denser neighborhoods where traffic volumes are higher, thus increasing exposure to traffic; however, this requires more research as the reviewed studies did not adjust for traffic volume.

This review uncovered research on many individual risk factors, but evidence from single studies does not allow us to draw many conclusions. However, these studies introduced some factors that warrant further investigation, such as bicycling purpose (eg, utilitarian versus play), presence of a preexisting mental disorder, and bicyclist visibility. For example, the use of reflective materials or lights was not associated with injury risk in children and adolescents,[37] but in an all ages study, 1 or more visibility aids (eg, headlights, reflectors, or fluorescent clothing) reduced the odds of a bicyclist MV collision resulting in hospitalization.[18] The finding that bicycling at a slow compared with a normal speed was related to injury was unexpected. The wide CI for this effect indicates a greater uncertainty of the result and suggests that this variable requires more study. The 1998 study that revealed no association between bicycling safety education and injury risk is supported by a recent systematic review that came to the same conclusion.[27]

Environmental Risk Factors

Many of the environmental variables related to time of day and weather were not associated with bicycling injury risk. An exception was the finding that riding on the weekend compared with weekdays increased risk of serious injury. This variable may relate to bicycling purpose (utilitarian versus play) and warrants further study.

Riding on the road, in rural compared with urban areas, and riding the majority of a trip on the sidewalk were environmental factors associated with increased bicycling injury risk. Injuries related to a MV collision were more severe than other bicycling injuries. Riding on pavement compared with other surfaces reduced injury risk. These results highlight the challenge of finding safe locations for children to bicycle. Children riding on the road (designed for MVs) or the sidewalk (designed for pedestrians) are required to adapt to environments not designed for bicycling. Children often ride for play versus taking a purposeful trip[48] and may not be attentive to the risks posed by riding alongside MVs. A study of bicycling environments revealed that greater traffic volume, intersections, presence of retail establishments, and path obstructions contributed to the risk of colliding with a MV.[20] Parachute, Canada's national injury prevention organization, maintains that children under age 10 are not physically and cognitively ready to ride their bicycles on the road with MV traffic.[49] In addition, although bicycling safety and skills education may increase children's bicycling safety knowledge, this does not translate into reduced injury risk.[27] Modifying the bicycling environment is a promising avenue for improving bicycling safety for children and adolescents.

Limitations of the Review

Although this systematic review was methodologically rigorous and comprehensive, it excluded studies published in languages other than English. However, the results incorporate studies from 4 of 7 world continents. It was not possible to do any meta-analyses because the studies were so varied in their risk factor and injury definitions. There were limitations to the quality assessment tool. We found that some of the items in the NOS scales were not suitable for assessing the methodological quality of injury research studies and so we made a few modifications to better suit the needs of our review. These changes were clearly described, but not validated.

Selection criterion 4, which assessed whether controls had a history of the disease (or in this review, previous bicycling injury), was not informative because injuries are not the same entity as chronic disease. Only 1 study reported it, so the quality scores were lower as a result. This criterion may also need to be modified for the tool to accurately assess the quality of injury studies in future reviews.

Limitations of the Included Studies

The included studies varied in methodological quality; the main weaknesses were inadequate definitions of study groups and the use of self-reported exposure and injury data. Medical records or administrative databases were the data sources for many studies, which limited the personal and bicycling exposure information available for analysis. Researchers should consider conducting personal interviews, which should be blinded to reduce the risk of misclassifying exposure status in case-control studies or outcome status in cohort studies.

CONCLUSIONS

Personal characteristics like age and sex were not consistently associated with bicycling injury risk

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and neither was bicycling safety education. Lower SES, which may be a proxy for more dangerous environments, was associated with increased injury risk and child and adolescent bicyclists incur more severe injuries when exposed to MV traffic. Given these findings, perhaps the best approach to prevent injuries would be to institute changes to transportation infrastructure that separate bicyclists from MVs. Where that is not feasible, we can minimize injuries by applying traffic-calming strategies to reduce MV traffic speed and volume. Ongoing evaluation of such strategies would ensure that the most effective ones could be applied to other jurisdictions for maximum public health gain. These strategies may also reduce the impact of low SES on injury risk, because children of all backgrounds would have safer places to ride. Creating safer bicycling environments will likely increase ridership, with the potential to establish lifelong active transportation habits and a healthier population. Future research should use strong study designs that incorporate a control group and adjust for bicycling exposure. Researchers should aim to use common variable definitions from previous research to allow for better comparisons between studies and possible meta-analyses.

ABBREVIATIONS

CI: confidence interval
ED: emergency department
GCS: Glasgow Coma Scale
ICISS: International Classification of Disease Injury Severity Score
MV: motor vehicle
NOS: Newcastle-Ottawa Scales
SES: socioeconomic status

manuscript, and critically reviewed the manuscript; Dr Bourdeaux assessed articles for inclusion and critically reviewed the manuscript; Dr Hagel conceptualized the review, supervised study selection and data analysis, and critically reviewed the manuscript; and all authors approved the final manuscript as submitted.

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