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.

Bicycling is an excellent form of physical activity for children and adolescents and an environmentally friendly form of transportation.\textsuperscript{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.\textsuperscript{3} In Canada, bicycling injuries are among the top 3 causes of unintentional injury hospitalizations for children ages 0 to 14.\textsuperscript{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.\textsuperscript{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.\textsuperscript{6} Health care costs arising from injuries to bicyclists of all ages in Canada in 2010 were estimated at nearly $300 million.\textsuperscript{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\textsuperscript{5} and a hospitalization rate of 12.7 per 100 000 for 0- to 19-year-olds.\textsuperscript{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.\textsuperscript{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.\textsuperscript{10–12} Regardless of the data source, the proportions and rates of bicycling injuries in boys are consistently greater than girls.\textsuperscript{8–10,13–17}

Bicycling injury risk factors have been widely studied by using all ages data,\textsuperscript{18–25} and 2 recent systematic reviews have focused on child and adolescent injury risk factors.\textsuperscript{26,27} These have revealed that child targeted bicycle helmet legislation is associated with decreases in mortality and head injuries after legislation;\textsuperscript{26} however, bicycle skills training interventions for children are not effective in reducing injury risk.\textsuperscript{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.\textsuperscript{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,\textsuperscript{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.\textsuperscript{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
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. 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. The NOS Cohort uses 8 scales (NOS) for nonrandomized studies. The NOS Cohort uses 8 criteria to evaluate selection bias, cohort comparability, and outcome assessment and has been used in another injury-related review. 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. 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.

**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. The NOS Cohort uses 8 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. The full-text of 568 articles were assessed for eligibility and 14 studies met the inclusion criteria. 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, 4 the United States, 4 Canada, 4 Norway, 4 and 2 in Taiwan. Study designs included 9 case-control and 1 retrospective cohort. Four did not self-identify as case-control studies, but conducted predetermined comparisons of severely and less severely injured bicyclists or comparisons of bicyclists with head injuries and those with other injuries. The majority were conducted in a pediatric population, and 3 studies included all age groups while providing subgroup data for children and adolescents. Five studies were published within the last 10 years, and 8 were published over 10 up to and including 20 years ago. The sources of injury data were ED records, trauma registries, administrative databases, self-reported survey data, coroners’ records, and police reported crashes. Bicycling injury comparisons included the following: injured with severely injured, with less severely injured,
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 Cohort31 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).

**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 sex35–40,45 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,23,36 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 injury39,40 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 al37 found that boys had a twofold greater risk of injury requiring hospital admission.
<table>
<thead>
<tr>
<th>Study</th>
<th>First Author, Year, Design</th>
<th>Setting Location, Time Period, Data Source</th>
<th>Participants: Age, Sample Size</th>
<th>Injury Outcome</th>
<th>Risk Factor</th>
<th>Results: OR, HR, Wilcoxon Rank Sum, $\chi^2$</th>
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<tbody>
<tr>
<td>Boufous, et al 2012, case-control</td>
<td>Australia; 2004–2008; Police reports of cycling related crashes on public roads</td>
<td>All ages, N = 6452</td>
<td>Case: severe injury (police reported death or injury requiring hospital transport); Control: cyclist in a traffic crash without severe injury</td>
<td>Age</td>
<td>Risk of severe injury (OR)$^a$</td>
<td>Age: 0–9 y: 1.0 (Ref); 10–19: 1.1 (95% CI: 0.75–1.63); Adjusted for helmet use, light condition, crash type, speed limit, urban/rural location and road curvature</td>
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<tr>
<td>Carlin et al 1995, population-based case-control</td>
<td>Australia; April 1993–April 1994; ED records, interviews with child and parent</td>
<td>5–14 y, Cases: 109 Controls: 118</td>
<td>Case: injured cyclist presenting to ED; Control: cyclist found by telephoning random numbers</td>
<td>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</td>
<td>Risk of injury (OR)$^b$</td>
<td>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: &lt;$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: 0.76–3.5); &gt;$40 000: 1.0 (Ref); Parent’s education: Primary: 1.8 (95% CI: 0.77–4.3); Secondary/tech: 1.0 (Ref); Occupational prestige: first tertile: 1.0 (Ref); second tertile: 1.5 (95% CI: 0.77–2.9); third tertile: 1.1 (95% CI: 0.55–2.1) Weekly distance: 0 km (play): 1.0 (Ref); 0–5 km: 0.56 (95% CI: 0.29–1.1); &gt;5 km: 1.1 (95% CI: 0.57–2.2) Weekly distance on busy streets: 0 km: 1.0 (Ref); 0–5 km: 1.7 (95% CI: 0.72–3.8); &gt;5 km: 1.5 (95% CI: 0.45–4.9); Weekly distance on local streets: 0 km: 1.0 (Ref); 0–5 km: 0.76 (95% CI: 0.41–1.4); &gt;5 km: 1.1 (95% CI: 0.51–2.2); Weekly distance on sidewalks: 0 km: 1.0 (Ref); 0–5 km: 0.83 (95% CI: 0.48–1.5); &gt;5 km: 3.1 (95% CI: 1.1–8.5) Weekly cycling time: 0–60 min: 1.0 (Ref); 61–180 min: 0.93 (95% CI: 0.54–1.6); &gt;180: 1.4 (95% CI: 0.74–2.5); Distance per week: 0–4 km: 1.0 (Ref); 4–12: 1.3 (95% CI: 0.69–2.4); &gt;12: 1.1 (95% CI: 0.59–2.1); Distance on sidewalks per week: 0–2 km: 1.0 (Ref); 3–5: 1.3 (95% CI: 0.63–2.7); &gt;5: 2.0 (95% CI: 0.95–4.0)</td>
</tr>
<tr>
<td>Carlin, et al 1998, population-based case-control</td>
<td>Australia; April 1993–January 1996; ED records, interviews with child and parent</td>
<td>9–14 y, Cases: 148 Controls: 130</td>
<td>Case: injured cyclist presenting to ED; Control: cyclist found by telephoning random numbers</td>
<td>Age, sex, income, parent’s education (81% mother), occupational prestige (1 highly skilled to 7 unskilled workers), total time bicycled per week, total distance bicycled per week, total distance on sidewalks per week, participated in school based bicycle education (parent reported)</td>
<td>Bicycle education$^a$: Yes: 1.57 (95% CI: 0.91–2.71); No: 1.0 (Ref); Adjusted for age, sex, income</td>
<td>Age: 9–11: 1.0 (Ref); 12–14: 1.1 (95% CI: 0.96–1.7)</td>
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$^a$ Adjusted for helmet use, light condition, crash type, speed limit, urban/rural location and road curvature.

$^b$ Adjusted for age, sex, income, parent’s education, Daniel’s scale of occupational prestige, 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.
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<tr>
<td>Hagel et al 2014, case control</td>
<td>Canada; May 2008–October 2010; structured interview, ED records</td>
<td>All ages; n = 2403; cases = 278</td>
<td>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</td>
<td>Age</td>
<td>Risk of injury (OR)</td>
<td>Age: &lt;13: 1.0 (Ref); 13–17: 2.88 (95% CI: 1.74–4.13)</td>
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<tr>
<td>Hagel et al 2015, case control</td>
<td>Canada; May 2008 October 2010; structured interview, ED records</td>
<td>&lt;18 y; n = 1470; cases = 119</td>
<td>Case: severe injury (bicyclist hospitalized after an ED visit); Control: nonsevere injury (bicyclist seen and discharged from ED)</td>
<td>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</td>
<td>Risk of severe injury (OR$^a$)</td>
<td>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)</td>
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<td>Study</td>
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<td>Li et al 1995; case-control</td>
<td>United States; 1988–1992; National Pediatric Trauma Registry</td>
<td>0–14 y, N = 2333 Case: HI; Control: other injury</td>
<td>Age, sex, preexisting mental disorder, collision with object, location</td>
<td>Risk of HI (OR) a</td>
<td>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, collision 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</td>
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<td>Macpherson et al 2004; case-control</td>
<td>Canada; 1994–1998; Hospitalization data from Canadian Institute for Health Information (CIHI)</td>
<td>5–19 y, N = 9367 Case: HI (injury to the head, face, and brain); Control: injury to other body parts</td>
<td>Age, sex, SES, riding in urban or rural area (population density was used to classify areas into 4 groups)</td>
<td>Risk of HI (OR) a</td>
<td>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: 1.09–1.38); 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.</td>
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<td>Mitchell et al 2015; case-control</td>
<td>Australia; 2001–2011; CrashLink (police-reported) data, hospital admissions records</td>
<td>≤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); Case 3: minor injury (ICISS ≥0.99); Control: minor injury (ICISS ≥0.99)</td>
<td>Time of crash, single cyclist crash, yes/daytime</td>
<td>Risk of Serious Injury (OR) a</td>
<td>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</td>
<td>Weekend: yes: 1.03 (95% CI: 0.62–1.73); no: 1.0 (Ref); adjusted for single vehicle crash 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: 0.78–2.48); no: 1.0 (Ref); adjusted for weekend, single vehicle crash Risk of fatal injury (OR)</td>
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<tr>
<td>Rivara, et al 1997; case-control</td>
<td>United States; 1992–1994 Questionnaire, ED and coroners’ records</td>
<td>All ages, N = 3343 Case: fatal injury; Control: nonfatal injury</td>
<td>Age</td>
<td>Risk of HI (OR) a</td>
<td>Helmet width of ≥2 cm larger than head width Helmet width: Boys: ≥2 cm: 15.6 (95% CI: 2.5–162.0); &lt;2 cm: 1.0 (Ref) Girls: ≥2 cm: 1.1 (95% CI: 0.1–4.3); &lt;2 cm: 1.0 (Ref)</td>
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<tr>
<td>Rivara, et al 1999; case-control</td>
<td>United States; Questionnaires, ED records, physical measurements</td>
<td>2–14 y, N = 126 helmeted cyclists Case: HI Control: other injury</td>
<td>Helmet width of ≥2 cm larger than head width</td>
<td>Helmet width: Boys: ≥2 cm: 15.6 (95% CI: 2.5–162.0); &lt;2 cm: 1.0 (Ref) Girls: ≥2 cm: 1.1 (95% CI: 0.1–4.3); &lt;2 cm: 1.0 (Ref)</td>
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<td>See and Lo 1997, matched case-control</td>
<td>Taiwan; Sep 1993–Jun 1995; Interviews, questionnaires, environmental audits</td>
<td>12–13 y, 197 cases matched with controls on sex, school grade</td>
<td>Case: bicycling injury in previous 12 mo; Control: riding bicycle in previous 12 mo with no accidents</td>
<td>Traffic volume, vehicle speed, obstacles</td>
<td>Traffic volume: More vehicles passed through case versus control sites (687 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</td>
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<tr>
<td>Senturia et al 1997, matched case-control</td>
<td>United States; Jun–Jul 1995; ED records, telephone interviews</td>
<td>7–18 y, Cases: 47; Controls: 42; Matched on age, sex, home location</td>
<td>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</td>
<td>Riding speed, riding location, distance from home, style of bicycle, riding companion, purpose of ride, stunt riding</td>
<td>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, stuntning 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, stuntning Distance from home: &gt;3/4 mile: 3.7 (95% CI: 1.1–12.5); ≤3/4 mile: 1.0 (Ref). Adjusted for speed, location, style, companion, purpose, stuntning 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, stuntning 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, stuntning 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, stuntning Stunt riding: Yes: 1.0 (Ref); No: 2.6 (95% CI: 0.5–10.3); Adjusted for speed, location, distance from home, style, companion, purpose</td>
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<tr>
<td>Wang et al 2009, matched case-control</td>
<td>Taiwan; Jan 2001–Dec 2002; Trauma Data Registry, telephone interviews</td>
<td>0–18 y, $N = 324$, Cases: 90</td>
<td>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</td>
<td>Proportion of severe HI ($\chi^2$) 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: 9.7%, $P = .001$ Centre of gravity: toward sidewalk: 7.8%, toward road: 73.0%, $P = .035$ Collision: large vehicle: 76.9%; pedestrian: 3.6%, $P = .04$ Bicycle machinery: lost control: 88%; tripped by roller chain: 1.9%, $P = .02$ Cause of accident: greater bicyclist speed: 44.3%; inattention/distraction: 6.4%, $P = .03$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 to clarify that the variable “single vehicle crash” in tables 3 and 5 of their manuscript referred to “single cyclist crash.”
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. Specific studies showed 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, but parental education was not associated with bicycling injury requiring hospital admission. 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. Two studies examined health-related variables: BMI was not associated with risk of bicycling injury requiring hospital admission, but presence of a preexisting mental disorder was associated with admission to a trauma center for a bicycling-related head injury.

Bicycling Equipment

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

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; 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. There was no association between bicycling with companions versus bicycling alone and injury risk. The 3 other bicyclist behavior variables were identified in single studies. Carlin et al 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 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. Bicycling a longer distance (ie, >1.2 km from home) in 1 trip was associated with greater injury risk, but total distance bicycled in a week was not. Bicycling for more than 3 hours per week was related to a shorter time to a child's first bicycling injury, and, in the preliminary analysis of 1 study, a greater injury risk (Carlin et al); however, final study results revealed no association. Bicycling frequency, defined as bicycling once per week, month, or year, was not associated with risk of an injury requiring hospital admission. Only 3 studies...
adjusted for bicycling exposure in their analyses.\textsuperscript{37,38,44}

\textbf{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,\textsuperscript{37} and spending 50\% or more riding time in play compared with none suggested a greater injury risk.\textsuperscript{35} Stunt riding was not associated with injury.\textsuperscript{44}

\textbf{Environmental Factors}

\textbf{Collision Involvement}

Two high quality studies demonstrated that colliding with a 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,\textsuperscript{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.\textsuperscript{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.\textsuperscript{39}

\textbf{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\textsuperscript{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).\textsuperscript{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.\textsuperscript{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.\textsuperscript{37} Riding in daylight\textsuperscript{37} or daytime,\textsuperscript{41} adverse weather conditions,\textsuperscript{37} and bicyclist-reported location speed limit\textsuperscript{37} were not associated with injury requiring hospital admission\textsuperscript{37} or serious (ICISS \leq 0.941) injury.\textsuperscript{41} Riding on the weekend compared with riding on weekdays was associated with serious (ICISS \leq 0.941) injury.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{43}

\textbf{DISCUSSION}

\textbf{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
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 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. 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. In addition, although bicycling safety and skills education may increase children’s bicycling safety knowledge, this does not translate into reduced injury risk. 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.
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

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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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