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Demographic and causal patterns in child cyclist head Injuries: Informing helmet test methods

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ABSTRACT

Children's cycle helmets are certified using the same impact conditions as adult helmets, which can overlook important factors contributing to child head injuries. Our objective is to identify common patterns in traumatic brain injury pathologies, age, sex, riding environment, cause of injury, helmet use, and helmet injury reduction in child cyclists to inform child-specific test methods.

We reviewed 48,074 head injury cases in cyclists under 17 years across 24 studies. An aggregate data *meta*-analysis was conducted to identify recurring patterns overall and in studies with a high proportion of severe injuries (n = 3,542 cases).

Cases most often involved male riders (71.8%, CI: 71.6–72.1%), aged 10–13 years (40.2%, CI: 39.1–41.3%), occurring on paved roads (75.0%, CI: 74.2–75.9%) without prior collision (84.4%, CI: 84.1–84.8%). Injuries were predominantly intracranial (73.7%, CI: 71.6–75.8%). Studies with mostly severe injuries included significantly more males, on-road incidents, motor vehicle collisions, intracranial haemorrhages, and skull fractures. Helmets reduced odds of head injuries (OR = 0.44, CI = 0.41–0.47), but the efficacy was lower for severe injuries (OR = 0.61, CI = 0.58–0.65), which contrasts most findings for adult helmets.

The identified factors associated with severe injuries in child cyclists, such as vehicle collisions and intracranial injuries with rotational mechanisms, are not represented in current child helmet test procedures. This work provides a foundation for further work aimed at quantifying representative head impact biomechanics in typical and severe child cycling incidents, with the ultimate goal of developing helmet test procedures tailored specifically to children.

1. Introduction

Impact testing of bicycle helmets is essential to ensure helmet designs provide sufficient protection during head impacts, which is their primary function. To be effective, these tests should simulate the common head impact conditions that occur in real-world cycling incidents, including representative impact locations, speeds, angles (Baker et al., 2023; Bonte et al., 2025; Bland et al., 2018; Bland et al., 2020; Abayazid et al., 2021; Baker et al., 2024), and relevant surface geometry, compliance, and roughness (Petersen et al., 2020; De Grau et al., 2020; Stitt et al., 2022). However, the head impact conditions experienced by children during cycling incidents have not yet been systematically characterised. This gap raises concerns about the real-world fidelity of current test methods for children's bicycle helmets.

Researchers (Jung et al., 2025; Li et al., 2024) and certification standards (BS EN 1080:2013) most often test children's bicycle helmets using the same impact conditions developed for adult helmets, without any evidence that they are alike. For example, the European standards for children's (EN 1080) (BS EN 1080:2013) and adult's (EN 1078) (BS EN 1078:2012+A1:2012) helmets each require the freefall drop of an EN 960 headform (BS EN 960:2006) at 5.4 m/s onto a rigid flat anvil and 4.57 m/s onto an anvil representing a rigid kerbstone, with a pass threshold of 250 g peak linear acceleration.

To the authors' knowledge, only one study has simulated real-world injury scenarios of child cyclists to quantify head injury biomechanics (McNally and Rosenberg, 2013). They used multibody dynamics software to recreate children falling from a bicycle, dropping from a kerb, colliding with a wall, and colliding with a vehicle. Head injury risk was

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quantified using the Head Injury Criterion (HIC) (Versace, 1971) and rotational acceleration. However, the study 1) did not report on head impact locations, speeds, or angles, 2) was based on incident data from a single regional hospital in Tasmania, and 3) generalised child anthropometry with a 6-year-old Hybrid III dummy model. Therefore, there is currently insufficient evidence to define representative impact conditions for testing children's bicycle helmets. The concern is that children differ substantially from adults in terms of cycling injury risk (Siman-Tov et al., 2012), behaviour (Schneier et al., 2006; Carlin et al., 1998; Wesson et al., 2008; McAdams et al., 2018; National Research Council (US), 2000), pathophysiology (Figaji, 2017; Ommaya et al., 2002; Dewan et al., 2018; Araki et al., 2017), and trauma recovery (Johnston, 2003; National Institute for Health and Care Excellence (NICE), 2023; Blackwell and Grell, 2023), which means their specific head injury mechanisms may not be represented in test methods derived for adults. The details of these differences are as follows.

1.1. Injury risk is high in child cyclists

Children represent a large proportion of cycling-related injuries and they experience head injury and TBI more frequently than adult cyclists (any head injury: 30.1% vs 18.7%, any TBI: 32.6% vs 23.6%) (Siman-Tov et al., 2012). Across Europe, cyclists represent 25% of all road traffic incidents resulting in child traumatic brain injury (TBI), with only pedestrians being more frequently injured (Riemann et al., 2020). In the United States, bicycles are the second most common consumer product associated with childhood injuries (Mehan et al., 2009; National Center for Injury Prevention and Control (US), 2017; Ali et al., 2019). These injuries also pose a significant threat to life with almost one quarter of cyclist fatalities in the United Kingdom (UK) being children and head injuries accounting for two thirds of these (Knowles et al., 2009).

1.2. Child behaviour and cognitive development influence risk

Children differ from adults in their cycling behaviours including more improper use of helmets (Siman-Tov et al., 2012; Linn et al., 1998; Klein et al., 2005; Towmey et al., 2001), novice riding skills (Hamann and Conrad, 2019; Zeuwts et al., 2020), immature hazard perception (Twisk et al., 2018), and limited compliance with traffic rules (Zeuwts et al., 2020). These factors also increase the likelihood of unsafe road entry, and motor vehicle collisions (MVC) with child cyclists most commonly occur when a child crosses into a line of traffic (Knowles et al., 2009). This risk is compounded because vehicle front-end geometries and driver sight lines are optimised for adult pedestrians and cyclists, making children harder to detect and increasing the likelihood that impact occurs higher on the body (Monfort et al., 2024; Peng et al., 2012).

1.3. Younger children are more susceptible to head injury with worse behavioural outcomes

Children are more susceptible to acceleration-deceleration head injuries because their heads are proportionally larger and heavier relative to body size (Ommaya et al., 2002; Farkas et al., 1992), and the cervical spine is underdeveloped with weaker neck muscles (Figaji, 2017; Ommaya et al., 2002; Prange and Margulies, 2002; Bandte et al., 2018; Cory et al., 2001). Younger children also have thinner and more deformable skulls (Ommaya et al., 2002; Goldsmith and Plunkett, 2004), which can cause higher tissue strains under the same impact conditions. The cerebral white matter in younger children also contains less myelin, which increases susceptibility to TBI and axonal injury (Ommaya et al., 2002; Araki et al., 2017; Goldsmith and Plunkett, 2004). Although neuroplasticity is generally greater in children than in adults (Blackwell and Grell, 2023; Dennis et al., 2014), child TBI is associated with long-term impairments in cognitive ability, academic performance, executive function, and behaviour (Anderson et al., 2009). These effects are often more pronounced when injury occurs at younger ages.

1.4. Well-defined injury patterns are required to inform representative helmet test procedures for children

To reflect that injury risk is greater in children than adults, particularly at younger ages, it has long been proposed that helmet standards should lower pass thresholds for child cycle helmets to 200 g and 150 g for children under 6 years old (Li et al., 2024; Lane, 1986; Cass and Gray, 1989). However, such changes are yet to be implemented, and it remains unknown if current test methods represent the impact conditions experienced by child cyclists. Identifying the patterns of head injury in child cyclists is essential for defining representative injury scenarios for future biomechanical research in the short-term and for guiding evidence-based revisions to helmet standards in the long-term. However, data on these patterns are currently siloed across different sources, and there is no cohesive evidence for patterns that these test methods should represent.

The aim of this study is to identify recurring demographic and causal patterns of head injuries in child cyclists. Specifically, this review addresses the following questions:

- What are the most prevalent head injuries in child cyclists, and does helmet use influence injury outcomes?
- How does head injury incidence vary by age and sex among child cyclists?
- What are the most common causes and riding environments associated with head injuries in child cyclists?
- Based on the injury patterns identified, what collision scenarios should be the focus of further biomechanical analyses aiming at developing representative helmet test methods?

2. Methods

2.1. Literature screening

Literature on child cyclist blunt trauma head injuries was collated from Google Scholar, PubMed, and Scopus databases using the operators: ("child*" OR "paediatric" OR "pediatric") AND ("cycl*") AND ("injur*") AND ("head" OR "brain") (Olivier and Creighton, 2017). Titles and abstracts were scanned for their relevance, and the number of sources was expanded by following in-text citations from relevant studies. 145 sources were reviewed in more detail beyond the abstracts (Fig. 1): 114 included data for child cyclist head injuries, 10 for adult or generic cycling head injuries, and 21 for non-cycling specific child head injuries. The authors and titles of all reviewed studies are listed in the supplementary material.

To ensure a representative view of the causes and outcomes of child cycling head injury and minimise bias, papers were excluded from the analysis if they focused exclusively on a single child age group (e.g., only teenagers), investigated only one injury cause mechanism (e.g., only vehicle collisions), duplicated data from another included study, originated from non-peer-reviewed sources, or lacked reasonable specificity for if data referred exclusively to children or head injuries. Twenty-four studies remained for the analysis, totalling 48,047 cases of child cycling head injuries from between 1987 and 2018. Geographically, 69% of data were from North America (26,150 cases from the United States, 7,189 from Canada), 30% from Europe (10,246 from Sweden, 3,762 from Denmark, 387 from Norway, and 22 from the UK), and $< 1\%$ (291) from Australia. Two studies totalling 3,804 cases were found from Asian nations (Shao et al., 2012; Oishi et al., 2022), though these all met the exclusion criteria. No data were found from South American or African sources.

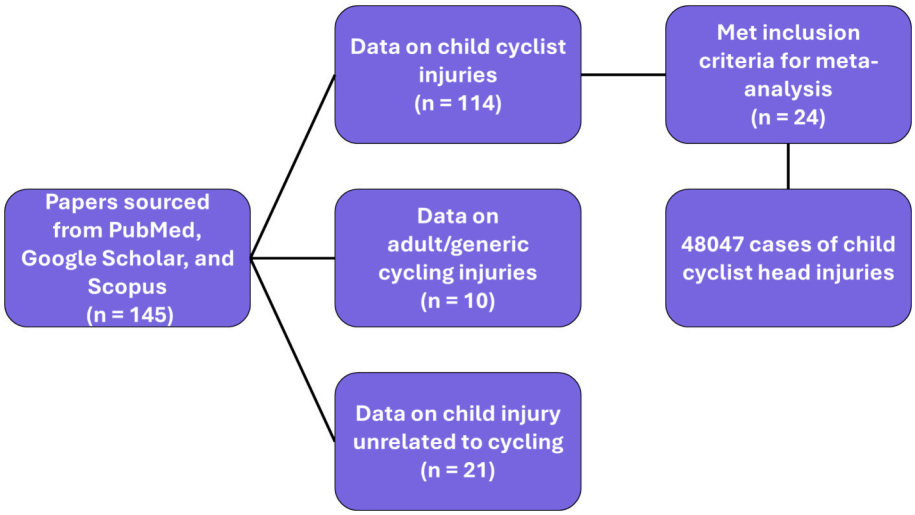


Fig. 1. The process for screening literature on child cyclist head injuries. From these, data were extracted to identify demographic and causal injury patterns through *meta*-analysis.

2.2. Meta-analysis

An aggregate data *meta*-analysis was conducted on data for: i) injury pathology details, ii) helmet use and efficacy, iii) sex, iv) age, v) environment of injury, and vi) cause of injury. The purpose was to identify the injury mechanisms and demographic factors most frequently represented in real-world injury data, as these represent the most relevant factors to consider in helmet impact testing.

The purpose of this study was not to review raw injury data, which in most cases was not reported in the manuscripts. Instead, we used the original classifications and terminologies from each source to make comparisons. There were disparities in how reviewed manuscripts defined various factors, including what constitutes a head injury, head injury severities, what caused head injury, and how ages were grouped together. We used the following definitions to minimise how this incurred variability in the data.

2.3. Definitions

Head injury: Where possible, blunt trauma head injuries were defined as involving structural damage to the cranium or an intracerebral abnormality. Injuries limited to the scalp were not considered in the analysis. Facial injuries were included only where sources did not distinguish them from head injuries and where they could not be identified and removed, to avoid inadvertently mitigating a head injury. Cases were not considered a head injury if they included neck injury within the category. Studies defined injury pathologies using different methods and coding, e.g. diagnostic imaging, admission status, classification system, etc. These could not be standardised without the raw data, so the authors original classifications had to be upheld.

Head injury severity: Different studies employed different metrics to define head injury severity, including the Injury Severity Scale (ISS), Abbreviated Injury Scale (AIS), Glasgow Coma Scale (GCS), level of hospital admission, and length of stay in hospital. Thresholds for "severe" injury also varied between the reviewed studies; for example, three studies using ISS applied > 6, >10, and > 15, respectively (Borglund et al., 1999; Gulack et al., 2015; Williams et al., 2018). Traditionally ISS > 15 is the threshold for severe injury (Palmer, 2007), though lifesaving interventions remain common at ISS below this (Vassallo et al., 2020). It was not possible to re-classify cases in the literature to this threshold because the raw data was not available. As a result, severity definitions were retained as defined by the original authors. Although this classifies some cases as "severe" that would otherwise be "moderate" by UK standards, it allowed for the inclusion of more data in the *meta*-analysis.

Age: Children were considered as aged 16 years and younger. At 16, full maturation of the neurocranium has occurred, individuals would typically be wearing adult helmets, and many children typically transition to motorised transport (Farkas et al., 1992; Jochems et al., 2021).

Environment of injury: The environments in which injuries occurred were described as 'on paved roads' or 'off-road', as these encapsulated 89% of cases. 'Off-road' includes incidents occurring on private land, bicycle tracks, footpaths, parks, etc. The remaining 11% of environments were classified as 'other' and were often when authors did not specify where incidents occurred.

Causes of injury: There is no consensus for describing the causes of collision with regards to cycling injury. We considered two conventions based on initial inspection of the data:

1. Impact occurred with the ground due to no-prior collision (NPC). This encompasses injuries due to a 'fall', 'loss of control', 'slip', 'drop' etc.
2. Impact involved prior collision (PC) with another object, such as motor vehicle collision (MVC), other bicyclists, stationary objects, and pedestrians. With these, it is assumed that collision with the object is the primary mechanism for injury, and not any subsequent fall.

Any incident not conforming to these or not specified by the authors was coded as 'other'. Some studies ambiguously described injury causes as "not caused by MVC", with no further details; these were excluded from the analysis so to not inadvertently misrepresent the incident.

2.4. Statistical analyses

Data for injury details, helmet use, sex, environment of injury, and cause of injury were analysed using a crude pooled analysis to identify frequenting patterns. Proportions within these were calculated from aggregated counts, with 95% confidence intervals (CI) derived using the normal approximation (Wald). This was considered appropriate given large sample size and significance $p = 0.05$. Throughout this analysis, all data refers to head injuries, unless otherwise indicated with a '†'. Analysis of environmental and causal patterns had to be determined from non-head injury specific data because very few studies specified where injury occurred on the body.

To infer trends based on injury severity without access to primary

data, studies in the analysis were categorised by the proportion of severe injury they contained. We defined studies as having few (FSI), considerable (CSI), or mostly severe injury (MSI) cases if < 33%, 33–66%, or > 66% of their data were self-described as 'severe', respectively. Chi-squared ($\chi 2$) was used to compare trends between severity categories, with $\alpha = 0.05$ significance. Pairwise comparisons were conducted on any significant findings, using Cramer's V (V) for effect size and Bonferroni correction for multiple comparisons.

Helmet efficacy was estimated using pooled odds ratios (OR) for the occurrence of head injuries between helmet wearers and non-wearers, consistent with previous *meta*-analyses of cycle helmets in adults (Olivier and Creighton, 2017; Attewell et al., 2001). Reported ORs and their CI were transformed to the logarithmic scale and combined using inverse-variance weighting (Higgins et al., 2024) to favour studies with lower standard error, then back-transformed for interpretation. The standard error of the log OR was derived from the reported confidence interval limits (Higgins et al., 2024). A random-effects model was applied using the DerSimonian–Laird method (DerSimonian and Laird, 1986) and heterogeneity was assessed using Cochran's Q and quantified with I^2. Where possible, this process was repeated with studies that isolated ORs for 'severe' head injuries.

Injury frequency could not be determined for specific ages because studies in the analysis reported them as groups with different limits and intervals, e.g. 'ages 5-9'. To estimate the prevalence of head injuries by age, we assumed the number of cases attributed to a group were shared uniformly across the ages within it. The cases attributed to each age were then aggregated across studies. To avoid skewing the results, studies were only included if they used age groups spanning five or fewer years, were specific for head injuries, and covered all ages 0–16 in their analysis (n = 3 studies, 8,019 cases). This was favoured over weighting each age year by the number of injuries found for that age in any one singular study, which would bias trends.

Results for age and sex were compared with and without including non-head injury specific data ('†') to assess sensitivity for when the location of injury was not specified. For sex, we qualitatively compared the difference in proportions for any significance and for age, we compared the relative number of injuries by age using Spearman's rank correlation. To assess bias from study size and identify potential outliers, a sensitivity analysis was performed for injury details, sex, and age by removing the largest studies until 50% of the total cases were excluded. From these, the only difference was seen for injury details, which is reported in the results while others are in the supplementary material. This check was not possible for environmental and causal patterns or trends with injury severity, due to too few studies within groups.

3. Results

3.1. Intracranial injuries are more common than skull fractures

Across studies, intracranial injuries were more common than skull fractures, with no individual study reporting more skull fractures than intracranial injuries (Table 1). When aggregated, Table 1 shows a ratio of more than 10:1 for intracranial injuries compared with skull fractures (9,669 vs 934 cases). However, Berg & Westerling (Berg and Westerling, 2007) contributed a disproportionately large number of concussive injuries. Their study analysed national inpatient discharge data, and concussion was the only category that included mild injury. Additionally, their use of ICD-9 850 permits concussion diagnosis from confusion, amnesia, and dizziness, thus inflating the number of assigned cases (Bazarian et al., 2006). Excluding Berg & Westerling, which contributed 86.8% of intracranial and 51.2% of skull fracture cases in the aggregated dataset, reduced the intracranial injury to skull fracture ratio to almost 3:1 (1,279 vs 456 cases)(Fig. 2).

Table 1
Prevalent head injuries in child cyclists according to 16/24 studies in the *meta*-analysis that best described them.

First Author, Date, Number of head injury cases	Number of head injury cases	Database (Region, Data collection period)	Description of child cyclist head injuries (n, %)
Studies with few severe injuries (FSI, n < 33%)			
Grimard et al., 1995 (Grimard et al., 1995)	189	Victorian Injury Surveillance System (VISS). (Australia, 1988–1992)	Included loss of consciousness (48, 25%), intracranial haemorrhage/ haematoma/ contusion (36, 19%), skull fracture (31, 16%), concussion (17, 9%), fatality (10, 5%), and others (3, 2%). There were also cases with only dysfunctional symptoms, such as amnesia or headache (81, 43%).
Finvers et al., 1996 (Finvers et al., 1996)	266	Children's Hospital Injury Research and Prevention Programme (CHIRPP). (Canada, 1991–1993)	Included concussion, skull fracture, "skull haematoma", and superficial but proportions were not specified. Head injuries accounted for the highest proportion of injuries (266, 38%).
Linn et al., 1998 (Linn et al., 1998)	715	CHIRPP. (Canada, 1991–1995)	Included superficial (72, 10%), concussion (62, 9%), other brain (13, 2%), skull fracture (12, 2%), and fatality (1, 0.1%). The head was the second most frequently injured location (715, 39%).
Macpherson et al., 2002 (Macpherson et al., 2002)	3426	Canadian Institute for Health Information (CIHI). (Canada, 1994–1998)	Head was the most frequently injured location (3426, 35%).
Shah et al., 2007 (Shah et al., 2007)	2194	2003 Healthcare Cost and Utilization Project's Kids' Inpatient Database (KID). (United States, Jan-Dec 2003)	Included "mostly" skull fracture and concussion, but proportions were not specified. Other intracranial injuries included laceration and haemorrhage. There were 40 (0.6%) fatalities, of which 37 (93%) were head injuries.
Berg et al., 2007 (Berg and Westerling, 2007)	9226	Swedish National Hospital Discharge Register. (Sweden, 1987–1996)	Included concussion (8390, 91%), skull fracture (478, 5%) and other head injuries (358, 4%).
Lindsay et al., 2014 (Lindsay and Brussoni, 2014)	2782	CHIRPP. (Canada, 2004–2009)	Included predominantly superficial or concussive injuries, others included intracranial injuries and skull fractures, although proportions were not specified.
Kaushik et al., 2015 (Kaushik et al., 2015)	597	Rochester Epidemiology Project (REP). (United States, 2002–2011)	Included abrasions (164, 28%), scalp lacerations (133, 22%), scalp contusions (120, 20%), brain

(*continued on next page*)

Table 1 (*continued*)

First Author, Date, Number of head injury cases	Number of head injury cases	Database (Region, Data collection period)	Description of child cyclist head injuries (n, %)
			injuries (75, 13%), skull fracture (23, 4%), and other injuries (63, 11%). Those requiring ICU admission included brain injures (9, 82%) and skull fractures (6, 55%). There were 2 fatal injuries: 1 subdural haematoma with *trans*-tentorial herniation and 1 dead on arrival.
McAdams et al., 2018 (McAdams et al., 2018)	7996	National Electronic Injury Surveillance System (NEISS). (United States, 2006–2015)	Included concussion, 'head' fracture, and any other intracranial injury, although proportions were not specified. Head injuries were the second most frequent amongst hospitalised cycling injuries (31.9%).
Engell et al., 2020 (Engell et al., 2020)	3762	Odense University Hospital (OUH). (Denmark, 1980–2014)	Included skull fracture, concussion, intracranial haemorrhage, and intracranial lacerations but the proportions were not counted. There were 18 fatalities (0.5%), all from head injuries.
Studies with considerable severe injuries (CSI, 33% < n < 66%)			
Li et al., 1995 (Li et al., 1995)	1252	National Pediatric Trauma Registry (NPTR). (United States and Canada, 1989–1992)	Included concussion (604, 48%), skull fracture (299, 24%, including 104 vault, 144 basilar, and 51 unspecified), intracranial haemorrhage (85, 7%, including 31 extradural, 25 subdural, 17 subarachnoid, and 12 unspecified), cerebral laceration/contusion (59, 5%), and other/ unspecified injuries (205, 16%). There were 40 fatalities, 36 due to head injuries. 30% of skull fracture cases also included intracranial haemorrhage but this source only counted the primary diagnosis.
Borglund et al., 1999 (Borglund et al., 1999)	144	Broward General Medical Center (BGMC) trauma registry. (United States, 1995–1998)	Included concussion, basilar skull fracture, intracranial haemorrhage, and superficial injuries but the proportions were not counted.
Bergenstal et al., 2012 (Bergenstal et al., 2012)	252	West Virginia Trauma and Emergency Medical System.	Included concussion (133, 53%), skull fracture (60, 24%), and intracranial

Table 1 (*continued*)

First Author, Date, Number of head injury cases	Number of head injury cases	Database (Region, Data collection period)	Description of child cyclist head injuries (n, %)
		(United States, 2008–2010)	haemorrhage (59, 23%).
Studies with mostly severe injuries (MSI, n > 66%)			
Shafi et al., 1998 (Shafi et al., 1998)	208	Children's Hospital of Buffalo. (United States, 1993–1995)	Included concussion (97, 47%), skull fracture (23, 11%), intracranial haemorrhage (15, 7%), cerebral contusion (10, 5%), and diffuse cerebral oedema (1, 0.5%).
Teisch et al., 2015 (Teisch et al., 2015)	17	One Level 1 Trauma Centre (Miami). (United States, 2000–2012)	Included concussion (10, 59%), skull fracture (1, 6%), and intracranial haemorrhage (2, 12%, 1 subarachnoid and 1 unspecified).
Carone et al., 2019 (Carone et al., 2019)	22	Paediatric Critical Care Unit, Nottingham Children's Hospital. (UK, 2011–2018)	Included extradural haematoma (7, 39%), subdural haematoma (5, 28%), contusion (4, 22%), skull fracture (1, 6%), intracranial haemorrhage (1, 6%), and diffuse axonal injury (1, 6%). 3 patients recovered without neurological deficit; 3 had mild deficit, 6 had moderate, 2 had severe, and 1 was fatal.

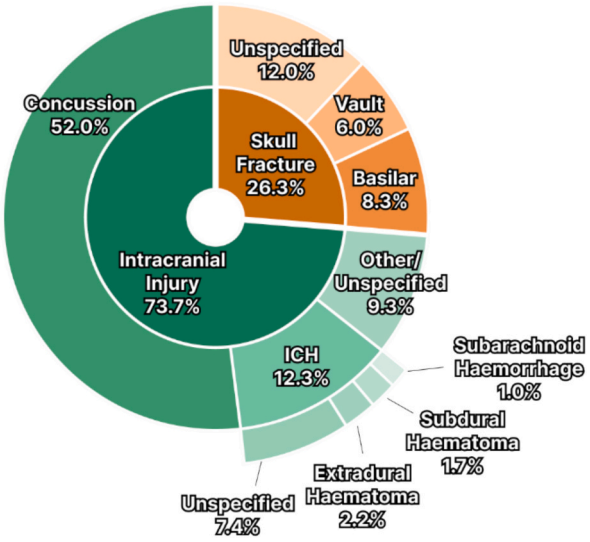


Fig. 2. Distribution of head injuries among child cyclists according to the literature in Table 1. Percentages represent the proportion of 1,735 head injury cases. This number is smaller than the total number of cases in Table 1 because data from Berg & Westerling (Berg and Westerling, 2007) were excluded to avoid overrepresentation of intracranial injuries. This number is smaller than the total cases in the analysis (Table 2) because few studies detailed head injuries. Counts for the types of ICH were obtained from only two studies (Li et al., 1995; Carone et al., 2019).

3.2. "Concussion" is the most reported injury

The observed frequency of intracranial injuries is largely attributable to the predominance of concussions in the data. Concussions were the most frequent injury in the analysis (52.0%, 95% CI: 49.7–54.4%), being reported in 13/15 studies. However, concussion was mostly attributed to mild outcomes (Berg and Westerling, 2007; Li et al., 1995; Macpherson et al., 2002; Shah et al., 2007).

Skull fractures were the second most common injury in the analysis (26.3%, 95% CI: 24.2–28.4%), reported in 13/15 studies. Only Li et al. (Li et al., 1995) provided detailed classifications of skull fractures, identifying basilar fractures as more frequent than vault (144 vs 104 cases). Findings from Borglund et al. (Borglund et al., 1999) may indirectly support this trend, as basilar fractures were explicitly highlighted in their analysis, whereas other cranial fractures were not specified.

Intracranial haemorrhage (ICH) was the third most common head injury in the analysis (12.3%, 95% CI: 10.8–13.9%), reported in 10/15 studies. Although most ICH cases were unspecified (66.4%), two studies provided detailed classifications. Li et al. (Li et al., 1995) reported 85 ICH cases, comprising 31 extradural haematoma, 25 subdural haematoma, 17 subarachnoid haemorrhage, and 12 unspecified cases. Carone et al. (Carone et al., 2019) reported 13 ICH cases, including 7 extradural, 5 subdural, and 1 unspecified. Other less frequently reported intracranial injuries included cerebral contusion or laceration (73 cases, 4 studies), and diffuse axonal injury or oedema (3 cases, 2 studies).

3.3. Skull fracture and intracranial haemorrhage are more common with severe injuries

Concussion, skull fracture, and ICH remained the most prevalent injuries when compared across studies with few (FSI), considerable (CSI), and mostly (MSI) severe injuries. There were significant differences between these groups, indicating that skull fractures and ICH are more associated with severe outcomes ($\chi^2(4) = 1293$, $p < 0.001$, $V = 0.24$). Concussions dominated in FSI (90.5%), while skull fracture (9.0%) and ICH (<1%) were rare. In CSI, concussion was the most common (59.4%), while fractures (29.0%) and ICH (11.6%) were notably higher. In MSI, concussion was dominant (71.3%), yet skull fracture (16.7%) and ICH (12.0%) were greater than in FSI.

3.4. Head injuries are common and the primary cause of fatalities

Two studies with a combined 3,692 cases found that injuries occur to the head more than anywhere else on the body (Finvers et al., 1996; Macpherson et al., 2002), while another two studies (8,711 cases) reported the head as the second most common location of injury (McAdams et al., 2018; Linn et al., 1998). In addition, out of a total of 112 fatalities reported in Table 1, 105 (93.8%) were attributed to head injury (Linn et al., 1998; Li et al., 1995; Carone et al., 2019; Grimard et al., 1995; Shah et al., 2007; Kaushik et al., 2015; Engell et al., 2020). Only one study specified the pathological cause of death, reporting a subdural haematoma with *trans*-tentorial herniation in a single case (Kaushik et al., 2015).

3.5. Helmets protect against head injuries, though helmet usage is low

Helmet use was recorded in 18 of the 24 studies in the analysis, totalling 23,357 known cases (Table 2). 16.2%† of children were reported as wearing a helmet at the time of incident (95% CI: 15.7–16.7%)†, and the range of helmet users within studies was 0.0–46.1%†. Overall helmet use changed very little when excluding studies that did not differentiate head injury from overall injury (17.6%, 95% CI: 17.1–18.2%). Helmet use also differed significantly across severity groups with moderate effect ($\chi^2(2) = 574$, $p < 0.001$, $V = 0.16$). The proportion of helmet users was higher in FSI (19%) than in CSI (4%) or MSI (7%).

8/24 studies used the same method to calculate odds ratios (OR) for sustaining a head injury when wearing a helmet (McAdams et al., 2018; Linn et al., 1998; Williams et al., 2018; Li et al., 1995; Finvers et al., 1996; Lindsay and Brussoni, 2014; Engell et al., 2020; Thomas et al., 1994). These totalled 12,502 known helmet use cases, 18.3% of which were helmet users. Helmets had a protective effect, with a mean OR = 0.44 (95% CI: 0.41–0.47) (Fig. 3) and between-study heterogeneity was negligible ($Q = 6.4$, $df = 7$, $I^2 = 0\%$). Two studies (Lindsay and Brussoni, 2014; Engell et al., 2020) analysed severe injuries separately, totalling 1,820 cases with 41.3% helmet users. These reported a lesser protective effect, with mean OR = 0.61 (95% CI: 0.58–0.65). Moderate statistical heterogeneity was observed, though this is unstable with only two studies ($Q = 2.3$, $df = 1$, $I^2 = 57\%$). Finally, all fatalities recorded alongside helmet use were in non-helmeted riders (34 cases, 4/24 studies) (Kaushik et al., 2015; Engell et al., 2020; Bergenstal et al., 2012; Shafi et al., 1998).

Three studies reported a difference in the head injury pathologies between helmet users and non-users, all with reduced risks of skull fracture and ICH in users (Grimard et al., 1995; Bergenstal et al., 2012; Shafi et al., 1998). For example, Bergenstal et al. (Bergenstal et al., 2012) found skull fracture in 3.2% of helmeted vs 17.4% of non-helmeted riders ($p = 0.04$), and intracranial haemorrhage in 0.0% vs 17.4% respectively ($p < 0.001$). All three studies identified concussion as the most common injury in helmet users, and none reported a significant reduction in concussion frequency compared to non-users.

3.6. Boys account for almost three times as many head injury cases as girls

Table 2 summarises demographic and causal findings of the 24 studies used in the *meta*-analysis. When aggregated across all studies, females were an almost 1:3 minority (28.2%, 95% CI: 27.94–28.41%, range across studies = 9–39%)†. This proportion remained similar when excluding studies that did not report head injury specific data (31.5%, 95% CI: 30.9–32.1%). The proportion of females differed significantly across severity groups, although the effect size was small ($\chi^2(2) = 121$, $V = 0.03$, $p < 0.001$)†. Females were slightly more represented in lower severity studies when comparing FSI (28.5%), CSI (24.0%), and MSI (22.9%) groups.

3.7. Ages 10–13 represent the largest proportion of head injury cases

The proportional distributions of head injuries and overall injuries across childhood ages were nearly identical (Fig. 4, $\rho = 0.98$, $p = < 0.001$). These show two large increases at age 5 and between 8–10 years. Head injuries were mostly those aged 10–13 years, with a collective 40.2% of cases (2,960/7,360, 95% CI: 39.1–41.3%). Ages 0–2 were the least common, with a collective 3.3% (95% CI: 2.9–3.7%). Age 5 years were 6.1% of cases (95% CI: 5.6–6.7%), and ages 6–9 were the second most common with a collective 29.4% of cases (95% CI: 28.4–30.5%). The shape of the head injuries-only curve in Fig. 4 did not differ when plotted for each injury severity group, implying the number of injuries by age seems independent of severity (ρ(FSI vs CSI) = 0.85, ρ(FSI vs MSI) = 0.90, ρ(CSI vs MSI) = 0.85, all $p < 0.001$).

3.8. Most injuries occurred on paved roads

6/24 studies reported the environments in which injuries occurred, totalling 10,232 cases (Linn et al., 1998; Li et al., 1995; Grimard et al., 1995; Thomas et al., 1994; Olofsson et al., 2017; Powell et al., 1997).

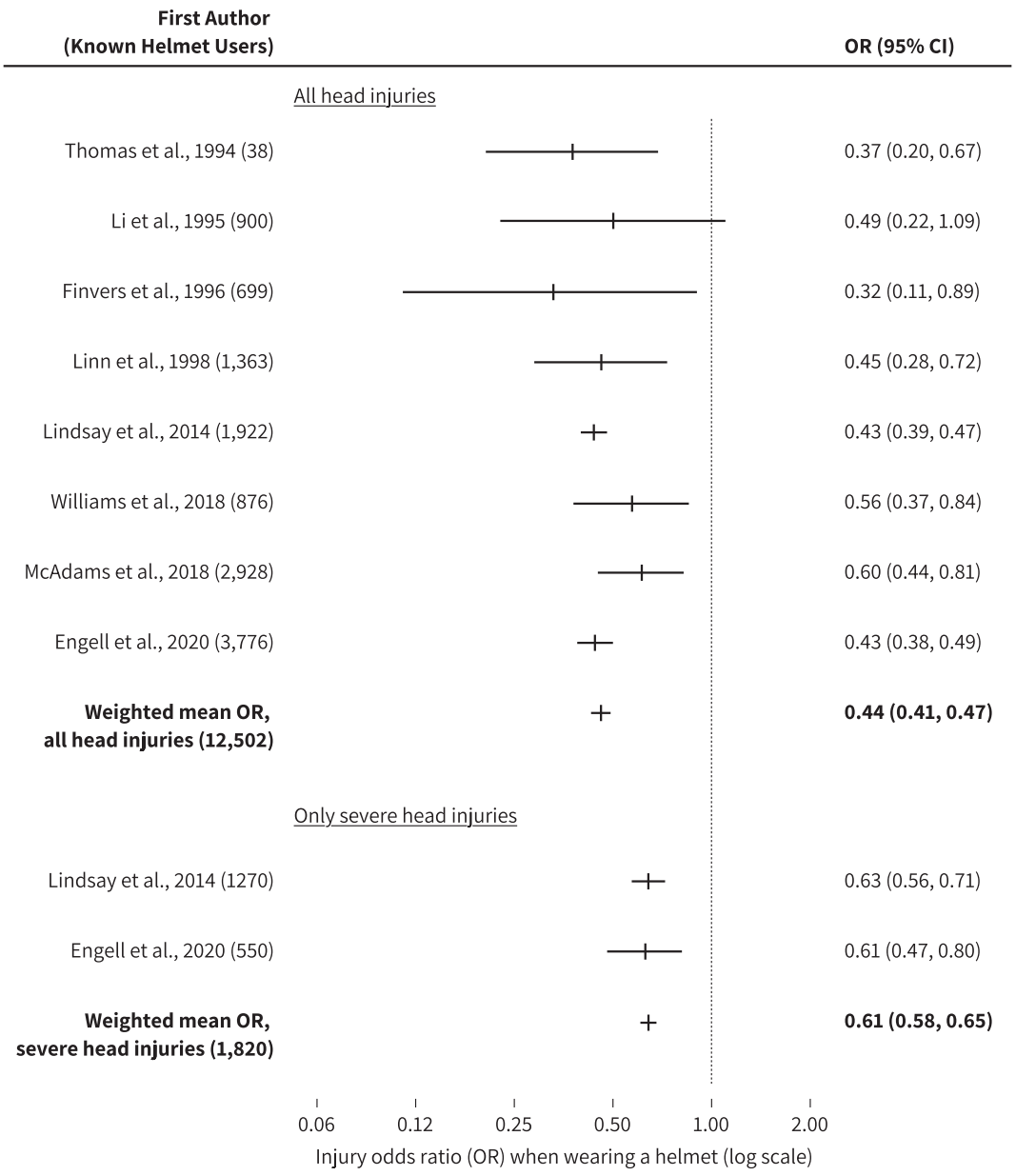


Fig. 3. Head injury ORs (95% CI) for child cyclists when wearing a helmet. Helmet use was known for 12,502 incidents, 1,820 of which were considered severe injuries. Mean odds ratios were weighted to give weight to studies with smaller confidence intervals.

However, 83.1% of this data were not specific to head injuries. Most cases were on paved roads (7,677 cases, 75.0%, 95% CI: 74.2–75.9%)†, followed by off-road (1468, 14.3%, 95% CI: 13.7–15.0%)†, and the remainder were 'other' or 'unclassified' (1087, 10.6%, 95% CI: 10.0–11.2%)†, as shown in Fig. 5. The proportion of injury environments differed slightly between the FSI and MSI groups ($\chi^2(2) = 121$, V = 0.12, $p < 0.001$)†. Off-road injuries were proportionally higher in FSI (FSI: 18.6% vs MSI: 10.9%) while paved-road injuries were more common in MSI (FSI: 69.7% vs MSI: 79.3%).

3.9. Most injuries occurred without prior collision

45,599 cases across 10 of the 24 studies had data for if injuries were caused by prior-collisions (PC) or no-prior collisions (NPC) (Linn et al., 1998; Grimard et al., 1995; Lindsay and Brussoni, 2014; Kaushik et al., 2015; Engell et al., 2020; Olofsson et al., 2017; Hansen et al., 2003). Only 3 of these studies (313 cases) were just on head injuries (Carone et al., 2019; Grimard et al., 1995; Thomas et al., 1994). As shown in Fig. 5; most cases were NPCs with 84.4%† (95% CI: 84.1–84.8%), while PCs were 15.6%† (95% CI: 15.2–15.9%). 'Other' or 'unclassified' injuries constituted only 0.13%† of cases and were not further considered in the analysis. The distribution of injury causes differed significantly between FSI and MSI ($\chi^2(1) = 3{,}157$, V = 0.27, $p < 0.001$) †. NPCs remained the most common cause of injury in both groups, though the proportion greatly decreased in MSI (FSI: 87.5% vs MSI: 54.0%)†. PCs were more common in the MSI group (FSI: 12.5% vs MSI: 46.0%)†.

3.10. Most incidents with prior collision involved motor vehicles

For incidents involving PC, MVCs were cited in all 10 studies (Linn et al., 1998; Grimard et al., 1995; Lindsay and Brussoni, 2014; Kaushik et al., 2015; Engell et al., 2020; Olofsson et al., 2017; Hansen et al., 2003), collisions with other bicycles were cited in 4 studies (Grimard et al., 1995; Kaushik et al., 2015; Engell et al., 2020; Olofsson et al., 2017), stationary objects in 3 studies (Carone et al., 2019; Thomas et al., 1994; Hansen et al., 2003), and pedestrians in 1 study (Kaushik et al.,

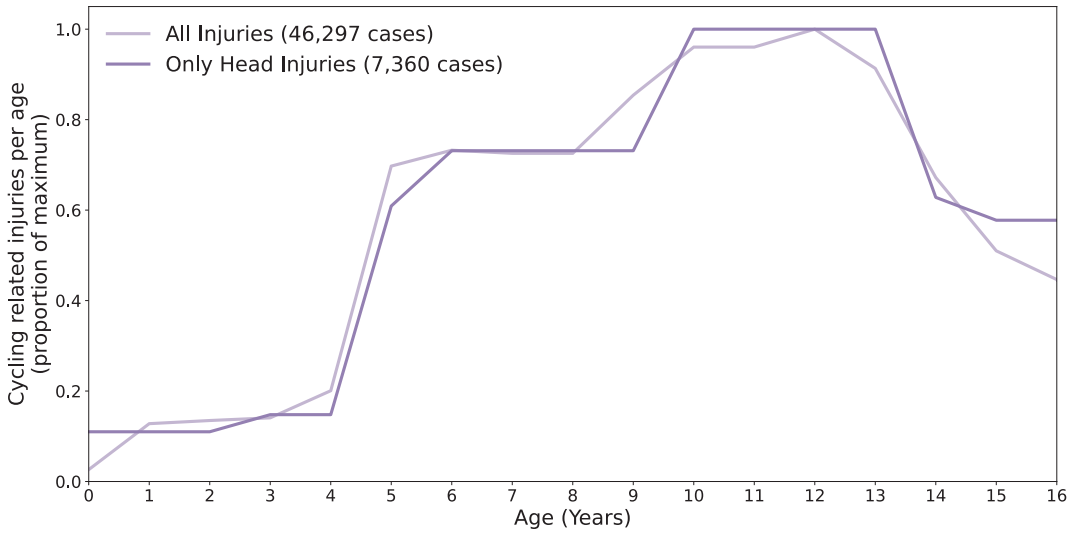


Fig. 4. Number of cycling related injuries per childhood age from 0-16 years relative to the number of incidents in the most frequently injured age. All injuries are from the thirteen studies with age group intervals of five or fewer years (Linn et al., 1998; Borglund et al., 1999; Li et al., 1995; Macpherson et al., 2002; Shah et al., 2007; Lindsay and Brussoni, 2014; Kaushik et al., 2015; Engell et al., 2020; Teisch et al., 2015; Thomas et al., 1994; Lee et al., 2005; Olofsson et al., 2017; Castle et al., 2012). Head injuries are from the three studies that were head injury specific and had data for every age between 0–16 (Linn et al., 1998; Shah et al., 2007; Lee et al., 2005). The two distributions are statistically similar ($p < 0.001$).

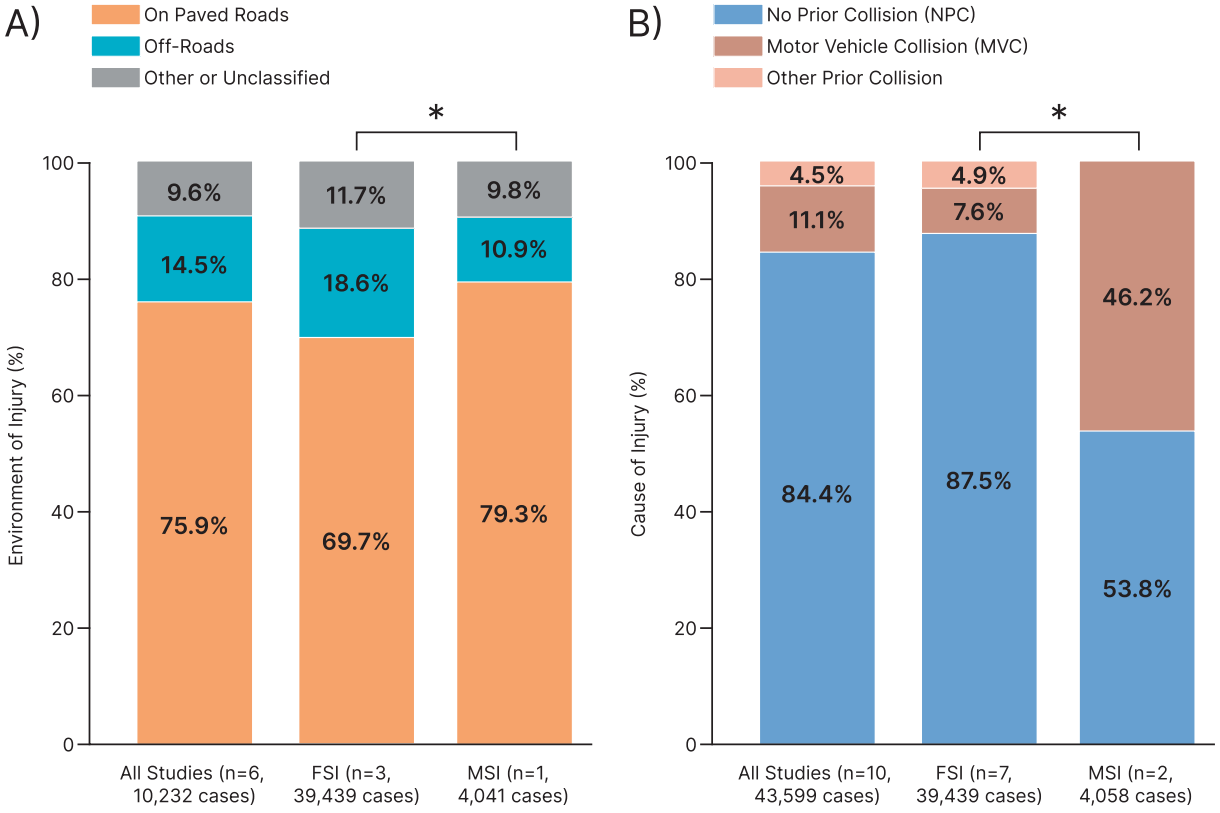


Fig. 5. The environments (A) and causes (B) of child cycling injuries across studies in the *meta*-analysis. There was significant difference in the distributions of the environments incidents happened in and what caused them between FSI and MSI (* = $p < 0.001$). Data in this figure are not specific to head injuries because of few cases in literature. Data for MSI was rarer than FSI, thus results shown are specific to the findings of only a few studies.

2015). Most PC cases involved MVCs (71.4%, 95% CI: 70.4–72.5%)†, followed by collisions with bicycles (25.6%, 95% CI: 24.5–26.6%)†, stationary objects (2.5%, 95% CI: 2.1–2.9%)†, and pedestrians (0.5%, 95% CI: 0.3–0.7%)†. Collectively, NPCs and MVCs constituted 95.5% of all injury causes (41,588 cases). The proportion of MVCs to NPCs increased significantly between FSI and MSI ($\chi^2(1) = 1,328$, $V = 0.18$, $p < 0.001$)†. While NPCs were the more common in the FSI group (FSI: 92.0% vs MSI: 53.8%)†, MVCs were more frequent in the MSI group (FSI: 8.0% to MSI: 46.2%)†.

Table 2
Summary of demographic and causal data relating to child cyclist head injuries found in literature (n = count, % of cases).

First Author (Data Region, Collection Period)	Study Size Total: 48,047	Sex	Helmet Use	Head Injury Severity*	Injured Ages, As Described in Years (n, %)	Description of Injury Cause and Environment (n, %)
		n Female (%)	n Wearing (%)	n Severe (%)		
Mostly Not Severe Injuries (n < 33%)						
Grimard et al., 1995 (Grimard et al., 1995) (Australia, 1988–1992)	189	63 (33%)	34 (18%)	40 (21%)	–	No prior collision (NPC) (96, 51%), motor vehicle collision (MVC) (55, 29%), collision with another bicycle (BC) (13, 6.9%), other (26, 14%). Cases occurred on paved road (125, 66%), off-road (29, 15%), other (35, 19%).
Finvers et al., 1996 (Finvers et al., 1996) (Canada, 1991–1993)	266	250 (36%)†	96 (14%)†	76 (29%)	Mean age = 8.9. †	–
Linn et al., 1998 (Linn et al., 1998) (Canada, 1991–1995)	715	408 (30%)†	300 (22%)†	172 (13%)†	5–9 (349, 49%), 10–14 (226, 32%), 0–4 (101, 14%), 15–19 (39, 5.4%).	NPC (1018, 72%), PC (non-MVC) (312, 22%), MVC (90, 6.3%). Paved roads (969, 80%), off-road (131, 11%), other (117, 9.6%).†
Macpherson et al., 2002 (Macpherson et al., 2002) (Canada, 1994–1998)	3426	2650 (27%)†	–	–	10–14 (4308, 55%), 5–9 (3466, 45%).†	MVC (1619, 17%). No further details for cause/environment.†
Hansen et al., 2003 (Hansen et al., 2003) (Norway, unspecified)	387	115 (30%)†	95 (25%)†	33 (9%)†	0–9 (195, 68%), 9–15 (91, 32%)	NPC (221, 57%), Collision with a stationary object (SC) (122, 32%), MVC (32, 8.3%).†
Lee et al., 2005 (Lee et al., 2005) (United States, 1991–2000)	5110	1005 (20%)	–	–	10–13 (1908, 37%), 5–9 (1740, 34%), 14–17 (1181, 23%), 0–4 (281, 5.5%).	"Non-MVC" (3361, 66%), MVC (1749, 34%). Urban areas (3201, 63%), suburban/rural (1909, 37%).
Shah et al., 2007 (Shah et al., 2007) (United States, Jan-Dec 2003)	2194	414 (19%)†	–	–	10–13 (872, 44%), 14–17 (498, 25%), 6–9 (494, 25%), 3–5 (99, 4.5%), 0–2 (15, <1.0%).	MVC (1697, 28%). The remainder were reported as 'unclassified cycling incident'. †
Berg et al., 2007 (Berg and Westerling, 2007) (Sweden, 1987–1996)	9226	3562 (39%)	–	–	Does not dichotomise age U16 years but shows more head injury cases for U16 (9226) than 16–50 years (8858).	"Non-MVC" (7138, 77%), MVC (2088, 23%).
Lindsay et al., 2014 (Lindsay and Brussoni, 2014) (Canada, 2004–2009)	2782	5712 (27%)†	887 (46%)	166 (7%)	9–12 (7547, 36%), 13–16 (6163, 30%), 5–8 (5222, 25%), 1–4 (1906, 9%).†	NPC (17087–18963, 82–91%), MVC (1229, 6%).†
Gulack et al., 2015 (Gulack et al., 2015) (United States, 2007 & 2010–2011)	4209	1741 (23%)†	544 (13%)	1241 (29%)	Median age = 11 (IQR 7—13).	–
Kaushik et al., 2015 (Kaushik et al., 2015) (United States, 2002–2011)	597	165 (28%)	87 (28%)	27 (5%)	5–9 (291, 49%) 10–14 (222, 37%), 15–18 (84, 14%).	NPC (1026, 86%), MVC (91, 7.6%), collision with a pedestrian (34, 2.9%), BC (9, 0.8%), other (29, 2.4%).†
Olofsson et al., 2017 (Olofsson et al., 2017) (Sweden, 1993–2006)	1020	1345 (36%)†	437 (43%)	34 (3%)	10–12 (1032, 28%), 4–6 (916, 25%), 13–15 (864, 23%), 7–9 (794, 21%), 0–3 (105, 2.8%).†	NPC (3184, 86%) BC (266, 7.2%), MVC (172, 4.6%). Paved road (2276, 61%) 42% of which were cycle/walking lanes (958), off-road (742, 20%), other (693, 19%)†
Williams et al., 2018 (Williams et al., 2018) (United States, 1999–2009)	876	223 (25%)	29 (3%)	218 (25%)	9–12 (323, 37%), 13–18 (317, 36%), 0–8 (236, 27%).	–
McAdams et al., 2018 (McAdams et al., 2018) (United States, 2006–2015)	7996	18,896 (28%)†	552 (19%)	1420 (18%)	10–14 (3526, 44.1%). The authors do not quantify cases of head injury for other age groups although they state 5–9 years had fewer cases than 10–14 yet more than 15–17.	"Non-MVC" (6686, 84%), MVC (1310, 16%).
Engell et al., 2020 (Engell et al., 2020)	3762	1406 (37%)	382 (10%)	545 (14%)	12–14 (1554, 41%), 5–8 (1228, 33%), 9–11 (994, 26%).	NPC (9971, 75%), BC (1462, 11%), MVC (1330, 10%) of which 133 (1%) were two wheeled†

(continued on next page)

Table 2 (*continued*)

First Author (Data Region, Collection Period)	Study Size Total: 48,047	Sex	Helmet Use	Head Injury Severity*	Injured Ages, As Described in Years (n, %)	Description of Injury Cause and Environment (n, %)
		n Female (%)	n Wearing (%)	n Severe (%)		
(Denmark, 1980–2014)						
Similar Not Severe and Severe Injuries (33% < n < 66%)						
Thomas et al., 1994 (Thomas et al., 1994) (Australia, 1991–1992)	102	23 (23%)	31 (32%)	45 (44%)	10–14 (50, 49%), 5–9 (47, 46%), 0–4 (5, 5%).	SC (49, 48%), NPC (34, 33%), MVC (19, 19%). Paved roads (70, 69%), off-road (24, 24%), other (7, 7%).
Li et al., 1995 (Li et al., 1995) (United States and Canada, 1989–1992)	1252	559 (24%)	10 (1%)	484 (39%)	10–14 (637, 51%), 5–9 (551, 44%), 0–4 (64, 5%).	MVC (623, 49%), BC (23, 2%), other (606, 48%). Paved road (1032, 82%), off-road (100, 8%), other (120, 10%).
Borglund et al., 1999 (Borglund et al., 1999) (United States, 1995–1998)	144	32 (22%)	19 (7%)	47 (33%)	10–12 (53, 37%), 7–9 (37, 26%), 13–15 (34, 24%), 4–6 (17, 11%), 1–3 (3, 2.1%).	MVC (113, 79%). No further details for cause/environment.
Bergenstal et al., 2012 (Bergenstal et al., 2012) (United States, 2008–2010)	252	94 (25%)†	7 (3%)	119 (47%)	Mean age = 9.3. Range = 1–14.	–
Mostly Severe Injuries (n > 66%)						
Powell et al., 1997 (Powell et al., 1997) (United States, 1986–1996)	2230	1011 (25%)†	126 (4%)†	578 (96%)†	5–14 (2131, 96%), 0–4 (99, 4%)	NPC (2177, 54%), MVC (1859, 46%). Paved road (3205, 79%), off-road (442, 11%), other (394, 10%). For children < 5 years: NPC (149, 68%), MVC (68, 31%). Paved road (100, 46%), off-road (85, 39%), other (34, 15%).†
Shafi et al., 1998 (Shafi et al., 1998) (United States, 1993–1995)	208	74 (36%)	31 (15%)	208 (100%)	Mean age = 7.	–
Castle et al., 2012 (Castle et al., 2012) (United States, 1992–2009)	1065	277 (16%)†	121 (11%)	1065 (100%)	10–14 (768, 46%), 6–9 (441, 26%), 15–17 (329, 20%), 2–5 (141, 8%), ≤1 (5, 0.3%).†	–
Teisch et al., 2015 (Teisch et al., 2015) (United States, 2000–2012)	17	15 (19%)	–	13 (76%)	10–14 (36, 45%), 5–9 (28, 35%), 15–17 (12, 15%), 1–4 (4, 5%), 0 (0). †	–
Carone et al., 2019 (Carone et al., 2019) (UK, 2011–2018)	22	2 (9%)	0 (0%)	22 (100%)	Mean age = 12.8.	MVC (15, 68%), NPC (6, 27%), SC (1, 5%).

* Severe injury as described by the authors or best interpreted. Different scales were used between sources, such as AIS, ISS, length of stay, etc.
† Data includes injuries other than head injuries.

4. Discussion

Our *meta*-analysis of 48,047 child cyclist head injuries shows distinctive demographic and causal patterns, as shown in Fig. 6. We found that most head injuries are to boys aged 10–13 years, occur on paved roads, and are caused by no prior collision such as a fall from loss of control. When prior collisions occur, they are mostly with motor vehicles, which are especially dominant in severe injury data. Concussive injuries are reported the most, though skull fracture and intracranial haemorrhage are more prevalent in severe injury data. Helmets reduce the risks of head injuries, though this effect is smaller for severe injuries. This review is the first to pool a large dataset of child cyclist head injuries from across literature. This provides foundation for representing child-specific injury patterns without assumptions based on adults, mixed-age cohorts, or individual studies. Our findings can inform improvements in helmet test methods and guide biomechanical analyses aimed at determining head impact conditions representative of child cyclists in real-world incidents.

4.1. Age is an important factor to consider in helmet tests

Children aged 10–13 years were the most frequently represented in injury data. This age corresponds with increased exposure to road traffic (Williams et al., 2018; Shah et al., 2007; Powell et al., 1997) and the lowest rates of helmet use (McAdams et al., 2018; Gulack et al., 2015; Olofsson et al., 2017; Dowd et al., 2002). New helmet test procedures to replicate the mechanics of head injuries for these ages would therefore provide the most societal relevance. However, by this age the cranium is almost developed to that of an adult (Farkas et al., 1992) and children begin wearing small/medium size adult helmets. Alternatively, incidence rates begin to rise significantly at age 5 years, where differences in stature, musculature, and relative head-to-body size lead to more severe injury than in adults when subject to collision (Figaji, 2017; Dewan et al., 2018; Araki et al., 2017; Goldsmith and Plunkett, 2004). Future studies are required to quantify the differences in head impact mechanics and injury tolerance between these younger and older children, to evaluate if it is fair to test their helmets the same way.

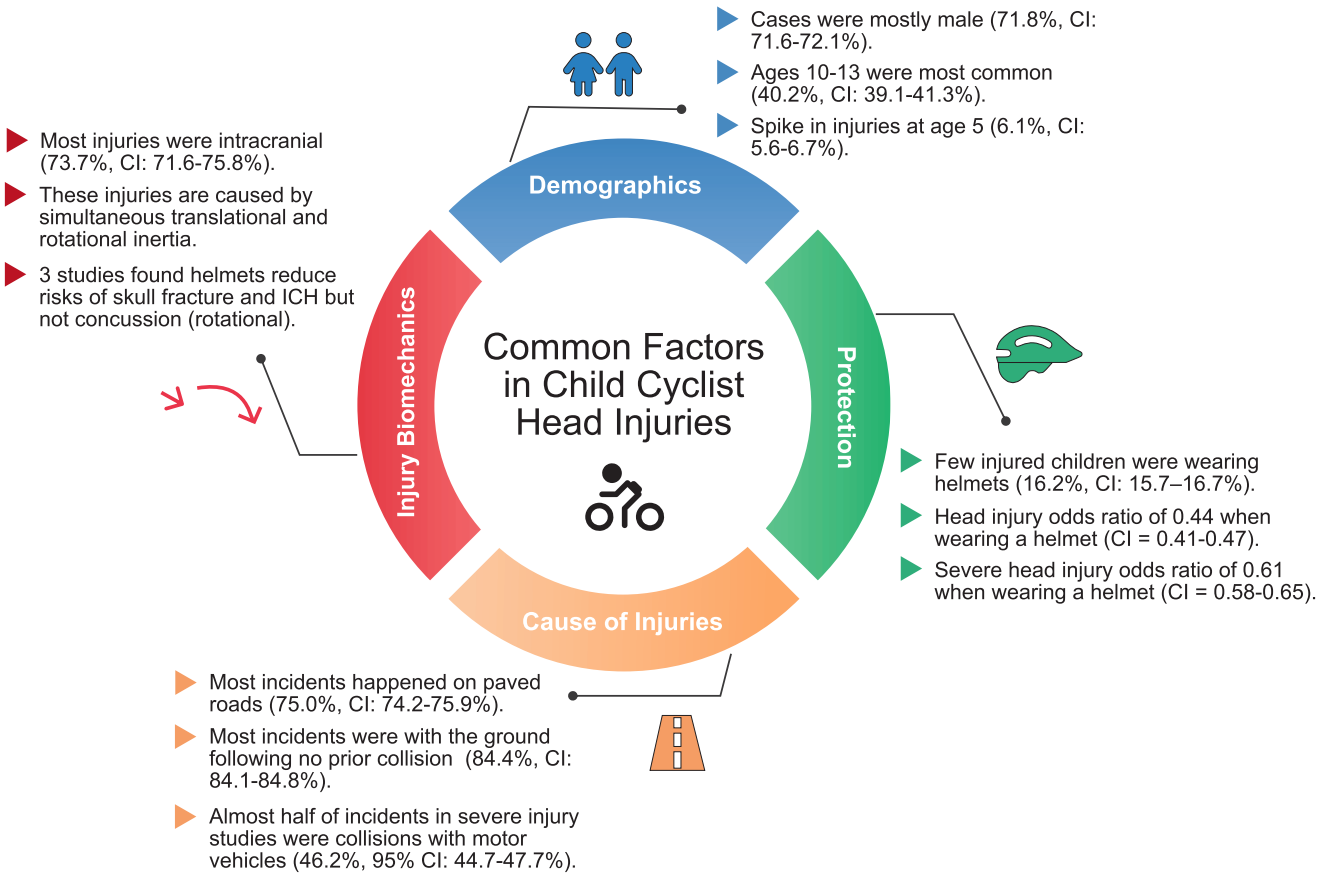


Fig. 6. A summary of common factors in child cyclist head injuries according to a *meta*-analysis of relevant literature. Results show proportions and 95th percentile confidence intervals (CI).

4.2. *More head injuries in boys likely reflects behavioural differences*

Our finding that male child cyclists are three times more frequently represented in injury data is consistent with patterns documented for cyclists across all ages (Siman-Tov et al., 2012; Amoros et al., 2012; Bambach et al., 2013; Dennis et al., 2013; Shack et al., 2022; Dodds et al., 2019). The male predominance likely reflects higher overall cycling participation, particularly in adolescence (Mehan et al., 2009; Evenson et al., 2003), greater risk-taking behaviour (Collins et al., 2013), and lower rates of helmet use (Engell et al., 2020; Collins et al., 2013; Briem et al., 2004; Failing et al., 2023; Joseph et al., 2017). There is no clear evidence that head injury tolerance differs between sexes during childhood, as it does in adults (Arambula et al., 2019; Gupte et al., 2019; Giordano et al., 2020). Consequently, androcentric bias currently appears less concerning in testing child's helmets than in adults.

4.3. *Child head impact speeds are expected to be lower than adults, though replication of speed alone does not capture their risks*

Most injuries were the result of falls due to loss of control, and MVCs were a significant cause of severe injuries. The flat and kerbstone anvils used in the current EN 1080 (BS EN 1080:2013) procedure are rigid and represent a range of surface areas. These are representative of most falls on paved roads and therefore most head injury conditions in children. In adult cyclists, head impact speeds due to falls are concentrated near 6 m/s (Baker et al., 2023; Peng et al., 2012; Bourdet et al., 2012; Bourdet et al., 2014) and are mostly a factor of travel speed, hip height, and bicycle roll angle (Bourdet et al., 2012). Head impact speeds in MVCs are concentrated around 9 m/s[1] and risk is mostly determined by the vehicles speed (McNally and Rosenberg, 2013; Strotmeyer et al., 2020; Kim et al., 2007). As a result, research-led helmet ratings test at higher speeds (Bland et al., 2018; Bland et al., 2020; Abayazid et al., 2021; Baker et al., 2024). Children generally cycle at lower speeds (Thompson et al., 1997) and have a lower hip height, so their head impact speeds are expected to be lower than in adults. Similarly, studies of pedestrian-vehicle collisions found that 6-year-old children have a 21% lower head impact speed on average than adults (Peng et al., 2012). Therefore, the current impact velocities of 5.4 m/s and 4.57 m/s in EN 1080 (BS EN 1080:2013) are likely closer to head impact speeds in children than they are in adults.

However, children in the case of MVCs are more likely to have head impact with the front-end geometry instead of more compliant surfaces like the windshield (Peng et al., 2012). This significantly increases injury risk despite a lower head impact speed, thus considering speed alone when defining helmet tests would underestimate the relative risks they experience. Further biomechanical study of child head impact kinematics resulting from vehicle collisions would better inform at what speeds to test children's helmets, by adjusting the setup to match force transfer to the head instead of speed at impact. This would also help to inform likely head impact locations and anvils, which the analysed literature does not highlight.

4.4. *The need for testing rotational protection of children's helmets*

Current standards evaluate helmets for protection against skull fractures and focal injuries only. However, the high prevalence of intracranial injuries in child cyclists, specifically subdural and subarachnoid haematoma and diffuse axonal injury, indicate that helmet tests should incorporate rotational measures alongside linear to more

comprehensively evaluate head injury risk (Viano and Parenteau, 2015; Depreitere et al., 2006; Zhang et al., 2004; Zhang et al., 2008; Wu et al., 2021; Kleiven, 2007). Additionally, isolated skull fractures are generally less clinically concerning in children than in adults due to higher neuroplasticity in children (National Institute for Health and Care Excellence (NICE), 2023).

Lower pass/fail thresholds of 200 g and 150 g for children under six years (Li et al., 2024; Lane, 1986; Cass and Gray, 1989) have been suggested for children's helmet standards, though there has been little consideration for rotational thresholds. Li et al (Li et al., 2024) suggest that rotational inertia may not impart greater brain strain in children and imply adult thresholds may be suitable for children. However, this is mostly informed from analysis of smaller head sizes and may overlook critical age-dependent variations in grain density and grey matter volume (Bethlehem et al., 2022). Further study of brain tissue mechanics in children at younger ages but using more high-fidelity models (Ghajari et al., 2017) would help to define specific injury risks and refine pass/fail thresholds.

4.5. Helmets are effective at reducing injury risk but less so for severe injuries

We found a mean 55% reduced odds of any head injury in child cyclists when wearing a helmet. This is similar to that reported for cyclists of all ages in previous *meta*-analyses (Olivier and Creighton, 2017; Attewell et al., 2001; Thompson et al., 1999; Elvik, 2011). In contrast, we found the reduction in odds of head injury in child cyclists was weaker for severe injuries (37%), whereas adult studies have generally reported equal or greater protection for severe injuries (Olivier and Creighton, 2017; Attewell et al., 2001; Thompson et al., 1999.). Our severe injury estimate is based on 1,820 head injury cases from only two studies and should therefore be interpreted as preliminary. However, it is noteworthy that an additional study of only MVCs, which was therefore excluded from our *meta*-analysis, supports our finding that helmet protection for severe injuries is lower in children (Strotmeyer et al., 2020). This pattern is likely a result of current limitations in child helmet design and their testing, and to be compounded by children's lower injury tolerance (Figaji, 2017; Dewan et al., 2018; Araki et al., 2017; Goldsmith and Plunkett, 2004), greater helmet misuse (Siman-Tov et al., 2012; Linn et al., 1998; Klein et al., 2005; Towmey et al., 2001), or poorer fit (Rivara et al., 1999).

5. Limitations

The distributions identified for age and injury details should be interpreted as indicative patterns and not exact epidemiological rates due to inconsistent definitions across studies. Concussion diagnoses are expected to be particularly heterogenous; as a symptom-based diagnosis with no structural brain-pathology they can cause significant confusion (Sharp and Jenkins, 2015) and are subject to over-classification in mild injuries and under-reporting in clinical imaging. Moreover, intracranial pathologies may be underrepresented in the literature because they are often undetectable on acute-stage CT (Bourke et al., 2022) and they are sometimes coded as secondary to fractures in polytrauma cases (Li et al., 1995). Despite this uncertainty, consistent reporting of intracranial injuries across multiple datasets highlights rotational forces should be considered in helmet testing.

The purpose of this study was not to estimate population-level injury risk but to identify the patterns most frequently represented in real-world injury data and highlight factors to consider in children's helmet performance testing. Measures of cycling exposure (e.g., riding frequency, travel distance, and riding duration) were not consistently reported across the analysed studies, preventing synthesis of exposure-adjusted injury rates. Consequently, the patterns identified here inherently reflect differences in exposure within the underlying datasets.

Findings for the environments and causes of incidents were reported on data for all injuries rather than head injuries alone. While this means the exact proportions for head-injury scenarios may differ, we expect the trends are likely to be representative. This is because several of the largest datasets reported head injuries as more than half of all cycling injuries (Berg and Westerling, 2007; Li et al., 1995; Kaushik et al., 2015; Castle et al., 2012; Powell et al., 1997) and we observed no differences in sex or age distributions between head-injury and all-injury subsets.

Recent increases in the use of electrically assisted bicycles and e-scooters may alter injury mechanisms in future datasets (Janikian et al., 2024; Posirisuk et al., 2022). However, these vehicles involve different speeds, masses, and regulatory classifications than conventional bicycles and were therefore outside the scope of the present review. Future epidemiological studies could investigate whether emerging micro-mobility use changes the injury patterns observed in children and how this effects helmet design.

Only 14% of head injuries in the included literature were classified as severe, so there were fewer studies and cases in the MSI than the FSI group. However, these severity groups effectively differentiated studies which mostly analysed broader trauma registries (FSI) and those which analysed specialised trauma centres (MSI). Comparisons between severity groups are therefore more influenced by individual studies than overall findings and may reflect specific populations rather than generalised scenarios.

6. Conclusion

This review demonstrates that head impact scenarios in child cyclists have typical demographic and causal patterns. Therefore, the following key takeaways guide how biomechanical studies and helmet test procedures can represent realistic head injury scenarios in child cyclists:

- Males are more frequently injured than females but there is limited knowledge of differences in head injury tolerance between them in children.
- Ages 10–13 years are the most frequently injured, though they have relatively similar physiology to adults. Ages 5–6 years are when injuries first become prevalent, with physiology more different to an adult.
- Most incidents occur on paved roads with no prior collision, such as a fall from loss of control.
- When prior collisions occur, they are mostly with motor vehicles and are associated with more severe injury outcomes.
- Current cycle helmets are potentially less effective at reducing severe injuries in children than they are in adults.
- Intracranial injuries are highly common in children and therefore rotational measures should be considered in helmet impact assessments.

These conclusions provide a foundation for future research aimed at quantifying head impact biomechanics in typical and severe child cycling incidents, with the ultimate goal of developing helmet test procedures tailored specifically to children.

CRediT authorship contribution statement

William Dawber: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Claire E. Baker:** Writing – review & editing, Validation, Funding acquisition. **David Sharp:** Writing – review & editing, Validation. **Shruti Agrawal:** Writing – review & editing, Validation. **Mazdak Ghajari:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aap.2026.108545.

Data availability

Data used in this article can be found online at https://doi.org/10.1016/j.aap.2026.108545.

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