



Review article

Bicycle injuries: A systematic review for forensic evaluation

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ABSTRACT

Bicycles are employed as means of transportation across various age groups, from young students to the elderly, for work, education, health, and leisure trips. Despite not achieving high speeds, bicyclists remain vulnerable to severe and even fatal injuries when they are involved in traffic accidents. Although the rising awareness of ecological issues and traffic law enforcement mean that cyclists are increasingly susceptible to road traffic crashes and injuries. Injuries resulting from a traffic accident involving cyclists can show distinct and specific characteristics depending on the manner of occurrence. The aim of this study is to provide a systematic review of the literature on injuries sustained in cyclists involved in road accidents describing and analysing elements useful for forensic assessment. The literature search was performed using PubMed, Scopus, and Web of Science from January 1970 to March 2023. Eligible studies have investigated issues of interest to forensic medicine about traffic accidents involving bicycles. A total of 128 studies satisfied the inclusion criteria and were categorized and analyzed according to the anatomical regions of the body affected (head, neck, thoraco-abdominal, and limb injuries), and the assessment of lesions in reconstruction of the bicycle accident was examined and discussed. This review highlights that injuries resulting from a traffic accident involving cyclists can show distinct and specific characteristics depending on the manner of occurrence and the energy levels involved in the crash. The assessment of injuries offers valuable insights that integrated with circumstantial and engineering data perform the reconstruction of accident dynamics.

1. Introduction

Bicycles are employed as means of transportation across various age groups, from young students to the elderly, for work, education, health, and leisure trips [1–3]. Despite not achieving high speeds, bicyclists remain vulnerable to severe and even fatal injuries when they are involved in traffic accidents. This vulnerability is primarily attributed to their limited protection and the fact that helmet usage is not mandatory [2–7]. In the last years, bicycling is growing in popularity because of global introduction of environmental antipollution policies and sustainable mobility [3,8]. Although the rising awareness of ecological issues, the general neglect of cyclists' needs in road design, land-use planning and traffic law enforcement mean that cyclists are increasingly susceptible to road traffic crashes and injuries [3]. Despite efforts to promote helmet use and make changes to bicycle infrastructure over the years, bicycle-related trauma continues to occur at a higher frequency [8,9].

Injuries resulting from a traffic accident involving cyclists can show

distinct and specific characteristics depending on the manner of occurrence. Therefore, to help reconstruct the mechanisms of such trauma, a systematic review of studies reporting injuries sustained in cyclists involved in road accidents was conducted with the aim of describing and analyzing elements that are useful for forensic assessment. This includes features of reported injuries, their role in causing death, and their relevance in reconstructing the dynamics of the accidents.

2. Materials and methods

An electronic search was performed in 3 databases: PubMed, Scopus, and Web of Science. Keywords related to the study aim and included in the search string were: (bike OR bicycle OR bicycling) AND (traffic accident OR road traffic OR motor vehicle OR crash) AND (injury OR wound OR death OR fatal outcome). The Preferred Reporting Items for Systematic reviews and Meta-analyses (PRISMA) guidelines were used [10].

The English language and time interval of publication, from January

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1970 to March 2023, were applied as filters. All studies that investigate the characteristics of injuries produced during traffic accidents involving bicycles were included. This included studies conducted in the forensic field which involved autopsy of victims. Additionally, studies conducted in clinical settings, involving both living and deceased subjects, from which information on the distribution and production characteristics of injuries could be obtained, were also included. This review did not extract diagnostic or therapeutic implications from the various types of injuries examined. Articles concerning electric bikes were not included.

Articles from the electronic search were examined to remove duplicate records. Titles and abstracts were then screened to exclude articles that did not meet the inclusion criteria. Screening was performed independently by two reviewers; discrepancies were resolved by the senior author. Full texts of included articles were retrieved and analysed. The bibliography of included articles was cross-referenced to find additional relevant articles (Fig. 1).

The following details were collected: authors' names, article titles, journal names, publication years, article types (prospective or retrospective studies, case reports, original articles), number of cases, injury location (head, neck, chest, abdomen, limbs), helmet use, fatal and non-fatal cases, method of injuries evaluation (autopsy, clinical and instrumental).

3. Results

The results of the literature search are summarized in Fig. 1. One hundred and twenty-eight studies met the inclusion criteria and were included in the review. The specific characteristics of each study are summarized in Table 1.

A total of 128 studies were included in the analysis. Among these, 81

(62 %) were retrospective studies, 30 (24 %) were case reports, 14 (11 %) were prospective studies and 3 (2 %) original articles.

Head injuries were the most extensively reported, (92/128), followed by lesions to limbs (68/128), chest and abdomen (chest 46/128; abdomen 63/128), and neck (33/118). The description of injury features was extracted from each article and thoroughly discussed.

Data on helmet use at the time of the accident were reported in 32 % of the total of the studies (41/128) and revealed that, based on the available data, only 22 % of the subjects was wearing helmets (5472/25354).

Data concerning the dynamics of the accident were reported in 48 % of the total number of studies (62/128) and showed that in 34 % of the cases the accident occurred due to a collision with motor vehicles (17,159/50,508), while in 9 % of the cases the subject had fallen by himself (4620/50508). The remaining data were related to further unspecified dynamics.

The forensic studies, where autopsies were conducted were 20 %. The clinical studies conducted primarily on both living and deceased patients excluding autopsies were 80 % and included the largest number of cases.

4. Discussion

In accidents involving cyclists, injuries can occur in various regions of the body through various mechanisms. These fatal or non-fatal injuries can provide important insights into the dynamics of the accident.

4.1. Head injuries

The head was the most frequent damaged body region in bicycle crashes [41,63,76], especially in children and adolescents within the

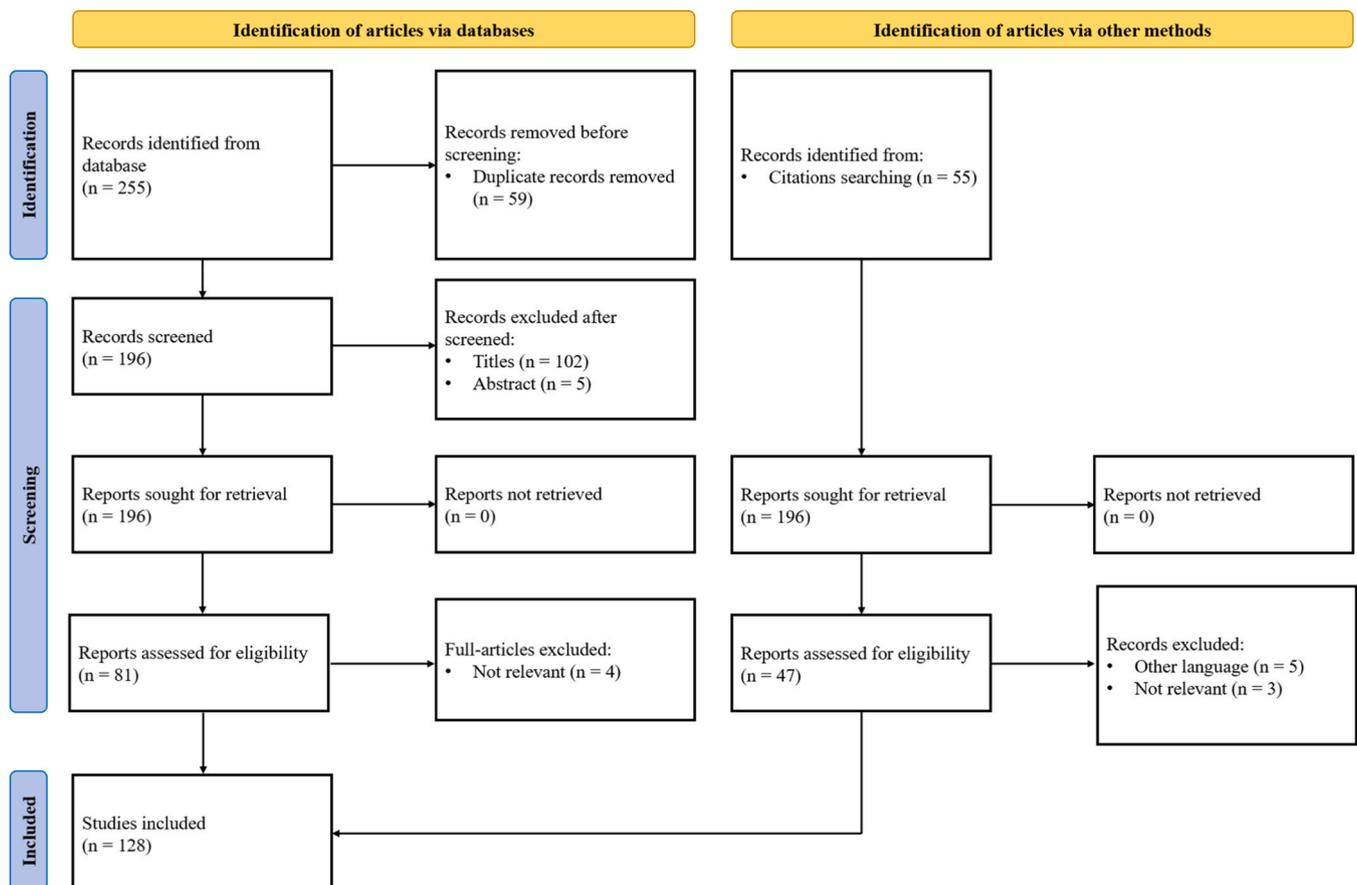


Fig. 1. PRISMA flowchart of the present review.

Table 1
Data from studies included in review. Abbreviations: N/A (data not available).

Author	Year	Study type	Cases	Injury location	Helmet use	Type of dynamics	Mortality	Method of injuries evaluation
Gourdie et al. [11]	1985	Case report	1	Abdomen, limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Lindqvist et al. [12]	1986	Retrospective study	93	Head	N/A	Collisions with motor vehicle: 81	Non-fatal	Clinical and instrumental
Mellion et al. [13]	1991	Original article	/	Limbs	N/A	N/A	N/A	N/A
Collins et al. [14]	1993	Retrospective study	238	Head	N/A	Collisions with motor vehicle: 78	Fatal	Clinical and instrumental
Chow et al. [15]	1993	Retrospective study	268	Head, neck, limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Oström et al. [16]	1993	Retrospective study	146	Head, neck	0	Collisions with a motor vehicle: 128	Fatal	Autopsy
Li et al. [17]	1995	Retrospective study	2333	Head	26 (data known for 1500 subjects)	N/A	Non-fatal: 2333 Fatale: 40	Clinical and instrumental
Bijur et al. [18]	1995	Prospective study	11,840	Head	N/A	N/A	Non-fatal	Clinical and instrumental
Yelon et al. [19]	1995	Retrospective study	84	Chest, abdomen, limbs	N/A	Collisions with a motor vehicle: 44	Non-fatal	Clinical and instrumental
Frank et al. [20]	1995	Retrospective study	311	Head, neck	12	N/A	Non-fatal: 296 Fatal: 15	Clinical and instrumental
McLean et al. [21]	1995	Prospective study	10	Head	N/A	N/A	Fatal	Autopsy
Tracy et al. [22]	1996	Case report	1	Abdomen	N/A	Fallen on his own	Fatal	Autopsy
Thompson et al. [23]	1996	Prospective study	700	Head	329	N/A	Non-fatal	Clinical and instrumental
Kronisch et al. [24]	1996	Retrospective study	16	Head, neck, chest, limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Kennedy et al. [25]	1996	Retrospective study	28	Head, neck, chest, abdomen	0	N/A	Fatal	Autopsy
Li et al. [26]	1997	Retrospective study	442	Head, limbs	293 (data known for 442 subjects)	Collision with motor vehicle	Non-fatal: 328 Fatal: 114	Clinical and instrumental
Clarnette et al. [27]	1997	Retrospective study	32	Abdomen	N/A	N/A	Non-fatal	Clinical and instrumental
Rivara et al. [28]	1997	Prospective study	3390	Head, limbs	1717	N/A	Non-fatal	Clinical and instrumental
Eilert-Petersson et al. [29]	1997	Retrospective study	1022	Head, limbs	44	Collision with motor vehicle: 73 Fallen on his own: 815	Non-fatal	Clinical and instrumental
Rivara et al. [30]	1997	Prospective study	3390	Head, chest, limbs	1717	N/A	Non-fatal	Clinical and instrumental
Puranik et al. [31]	1998	Retrospective study	211	Head, neck, chest, abdomen, limbs	3	Collision with motor vehicle: 174	Non-fatal: 205 Fatal: 6	Clinical and instrumental
Winston et al. [32]	1998	Prospective study	107	Head, neck, chest, abdomen, limbs	N/A	Collision with motor vehicle: 55 Fallen on his own: 31	N/A	Clinical and instrumental
Powell et al. [33]	1997	Retrospective study	4041	Head, abdomen, limbs	126	Collision with motor vehicle: 1253 Fallen on his own: 2788	Non-fatal: 3959 Fatal: 82	Clinical and instrumental
Harrison et al. [34]	1999	Prospective study	104	Head	15	N/A	N/A	Clinical and instrumental
Spitz et al. [35]	1999	Case report	1	Abdomen	N/A	Fallen on his own	Fatal	Autopsy
Gassner et al. [36]	1999	Retrospective study	562	Head	N/A	Collision with motor vehicle: 71 Fallen on his own: 472	N/A	Clinical and instrumental
Hitosugi et al. [37]	1999	Retrospective study	76	Head, neck	0	N/A	Fatal	Autopsy
Ushiyama et al. [38]	1999	Case report	1	Head	N/A	Fallen on his own	Fatal	Autopsy
Mine et al. [39]	2000	Retrospective study	26	Limbs	N/A	Fallen on his own: 18	Non-fatal	Clinical and instrumental
Nehoda et al. [40]	2001	Retrospective study	52	Abdomen	N/A	N/A	N/A	Clinical and instrumental
Boström et al. [41]	2001	Retrospective study	34,606	Head, chest, abdomen, limbs	N/A	Collision with motor vehicle: 9992	Non-fatal: 33,036 Fatal: 1570	Clinical and instrumental
Erez et al. [42]	2001	Retrospective study	76	Abdomen	0	N/A	Non-fatal	Clinical and instrumental
Thompson et al. [43]	2001	Original article	/	Head, chest, abdomen, limbs	N/A	N/A	N/A	N/A
Chow et al. [44]	2002	Retrospective study	97	Head, abdomen, limbs	97	Fallen on his own	Non-fatal	Clinical and instrumental

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Table 1 (continued)

Author	Year	Study type	Cases	Injury location	Helmet use	Type of dynamics	Mortality	Method of injuries evaluation
Gunji et al. [45]	2002	Retrospective study	5	Head, neck, chest, abdomen	N/A	N/A	Fatal	Autopsy
Klintschar et al. [46]	2003	Case report	1	Head, limbs	N/A	Collision with motor vehicle	Fatal	Autopsy
Mancel et al. [47]	2003	Case report	1	Abdomen	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Rosenkranz et al. [48]	2003	Retrospective study	222	Head, chest, abdomen	45	Collision with motor vehicle: 78	Non-fatal: 218 Fatal: 4	Clinical and instrumental
Depreitere et al. [49]	2004	Retrospective study	86	Head	3 (data known for 59 subjects)	Collision with motor vehicle: 44	Non-fatal: 83 Fatal: 3	Clinical and instrumental
Ng et al. [50]	2004	Case report	2	Head	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Ramírez et al. [51]	2005	Retrospective study	127	Head	N/A	N/A	N/A	Clinical and instrumental
Ahmad et al. [52]	2005	Case report	1	Head	N/A	Fallen on his own	Fatal	Clinical and instrumental
Davidson et al. [53]	2005	Retrospective study	293	Head, neck, chest, abdomen, limbs	61	Collision with motor vehicle: 73	Non-fatal	Clinical and instrumental
Tőro et al. [54]	2005	Retrospective study	45	Head, chest, limbs	N/A	N/A	Fatal	Autopsy
Heng et al. [55]	2006	Retrospective study	160	Head, chest, abdomen, limbs	16	Collision with motor vehicle: 72 Fallen on his own: 73	Non-fatal: 157 Fatal: 3	Clinical and instrumental
Bohmer et al. [56]	2006	Case report	1	Abdomen	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Orbell et al. [57]	2006	Case report	1	Abdomen	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Kim et al. [58]	2006	Retrospective study	399	Head, neck, chest, limbs	140	N/A	Non-fatal	Clinical and instrumental
Suri et al. [59]	2007	Retrospective study	42	Limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Buck et al. [60]	2007	Case report	2	Head, limbs	N/A	Collision with motor vehicle: 2	Non-fatal: 1 Fatal: 1	Clinical and instrumental
Agrawal et al. [61]	2007	Case report	1	Head	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Munkholm et al. [62]	2007	Retrospective study	25	Head, abdomen, limbs	N/A	N/A	Fatal	Autopsy
Richter et al. [63]	2007	Prospective study	4264	Head, neck, chest, abdomen, limbs	78	Collision with motor vehicle: 3113	Non-fatal: 4200 Fatal: 64	Clinical and instrumental
Eid et al. [64]	2007	Retrospective study	200	Head, limbs	2	Collision with motor vehicle: 28 Fallen on his own: 163	Non-fatal	Clinical and instrumental
Robertson et al. [65]	2008	Retrospective study	50	Head, chest, abdomen, limbs	5	N/A	Non-fatal	Clinical and instrumental
Lee et al. [66]	2008	Retrospective study	63	Head	N/A	Collision with motor vehicle: 13 Fallen on his own: 39	Non-fatal	Clinical and instrumental
Somville et al. [67]	2009	Case report	1	Abdomen	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Sikic et al. [68]	2009	Retrospective study	25,920	Head, neck, chest, limbs	N/A	N/A	Fatal: 47	Clinical and instrumental
Mohammadi et al. [69]	2009	Retrospective study	116	Head	N/A	N/A	Fatal	Autopsy
Chattopadhyay et al. [70]	2009	Case report	1	Head	N/A	Fallen on his own	Fatal	Autopsy
Yeung et al. [71]	2009	Retrospective study	698	Head, chest, abdomen, limbs	3	Collision with motor vehicle: 20	Non-fatal: 696 Fatal: 2	Clinical and instrumental
Klin et al. [72]	2009	Retrospective study	142	Head, chest, abdomen	N/A	Collision with motor vehicle: 45 Fallen on his own: 93	Non-fatal	Clinical and instrumental
Bener et al. [73]	2009	Retrospective study	490	Head, neck	N/A	N/A	N/A	Clinical and instrumental
Karaman et al. [74]	2009	Retrospective study	14	Abdomen	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Agarwal et al. [75]	2010	Prospective study	41	Limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Tin et al. [76]	2010	Retrospective study	/	Head, limbs	N/A	N/A	N/A	N/A
Airaksinen et al. [77]	2010	Retrospective study	216	Head, chest, abdomen, limbs	32	N/A	Non-fatal: 214 Fatal: 2	Clinical and instrumental
Scheiman et al. [78]	2010	Retrospective study	456	Head, neck, chest, abdomen, limbs	9 (data known for 22 subjects)	Collision with motor vehicle: 27	Non-fatal: 453 Fatal: 3	Clinical and instrumental
Lustenberger et al. [79]	2010	Retrospective study	2000	Head, limbs	N/A	N/A	Non-fatal: 1940 Fatal: 60	Clinical and instrumental

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Table 1 (continued)

Author	Year	Study type	Cases	Injury location	Helmet use	Type of dynamics	Mortality	Method of injuries evaluation
Yamamoto et al. [1]	2011	Retrospective study	307	Head	N/A	Collision with motor vehicle: 80	Non-fatal	Clinical and instrumental
Schmidt et al. [80]	2011	Case report	1	Head, neck	N/A	Fallen on his own	Fatal	Autopsy
Hassouna et al. [81]	2011	Case report	1	Limbs	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Klimek et al. [82]	2012	Retrospective study	40	Abdomen	N/A	N/A	Non-fatal	Clinical and instrumental
Galtés et al. [83]	2012	Case report	1	Head, neck	N/A	Collision with motor vehicle	Fatal	Autopsy
Hefny et al. [84]	2012	Prospective study	130	Head, limbs	0	Collision with motor vehicle: 85	Non-fatal: 128 Fatal: 2	Clinical and instrumental
Siman et al. [85]	2012	Retrospective study	5529	Head, neck, chest, abdomen, limbs	N/A	N/A	N/A	Clinical and instrumental
Huiszoon et al. [86]	2012	Case report	1	Head	N/A	Fallen on his own	Fatal	Autopsy
Alkan et al. [87]	2012	Retrospective study	8	Abdomen	N/A	N/A	Non-fatal	Clinical and instrumental
Júnior et al. [88]	2012	Retrospective study	556	Head	N/A	N/A	Non-fatal	Clinical and instrumental
Brand et al. [89]	2013	Retrospective study	518	Head, chest, abdomen, limbs	43	N/A	Non-fatal	Clinical and instrumental
Cevik et al. [90]	2013	Retrospective study	59	Head, chest, abdomen, limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Munivenkatappa et al. [91]	2013	Retrospective study	108	Head	N/A	Collision with motor vehicle: 60	Non-fatal: 100 Fatal: 8	Clinical and instrumental
Roberts et al. [92]	2013	Retrospective study	258	Head, neck, chest, limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Silberman et al. [93]	2013	Original article	/	Chest, abdomen, limbs	N/A	N/A	N/A	N/A
Yilmaz et al. [94]	2013	Retrospective study	500	Head, chest, abdomen, limbs	48	N/A	Non-fatal: 442 Fatal: 58	Clinical and instrumental
Venara et al. [95]	2013	Case report	1	Head, chest, abdomen, limbs	1	Fallen on his own	Fatal	Autopsy
Edirisinghe et al. [96]	2014	Retrospective study	328	Head, neck, chest, abdomen, limbs	N/A	N/A	N/A	Autopsy
Kose et al. [97]	2014	Case report	1	Limbs	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Hayakawa et al. [98]	2014	Case report	1	Head, limbs	N/A	Collision with motor vehicle	Fatal	Autopsy
Dinh et al. [99]	2015	Retrospective study	258	Head, neck, chest, abdomen, limbs	203	Collision with motor vehicle: 111	N/A	Clinical and instrumental
Dai et al. [100]	2015	Retrospective study	219	Abdomen	N/A	N/A	Non-fatal	Clinical and instrumental
Olds et al. [101]	2015	Retrospective study	42	Head, neck, chest	N/A	Collision with motor vehicle: 34	Fatal	Autopsy
Pederiva et al. [102]	2015	Case report	1	Abdomen	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Mak et al. [103]	2015	Retrospective study	15	Limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Goldstein et al. [104]	2016	Retrospective study	157	Limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Piras et al. [6]	2016	Retrospective study	335	Head, chest, abdomen, limbs	N/A	Collision with motor vehicle: 308	Fatal	Autopsy
Neumann et al. [105]	2016	Retrospective study	261	Head, neck, chest, abdomen, limbs	N/A	Collision with motor vehicle: 65	Non-fatal: 255 Fatal: 6	Clinical and instrumental
Gopinath et al. [106]	2016	Prospective study	238	Head, neck, chest, abdomen, limbs	N/A	N/A	N/A	Clinical and instrumental
Bil et al. [5]	2016	Retrospective study	129	Head	5	Collision with motor vehicle: 82	Fatal	Autopsy
Hitosugi et al. [4]	2016	Prospective study	55	Head, chest, abdomen	2	Collision with motor vehicle: 39	Fatal	Autopsy
Kotlyar et al. [107]	2016	Retrospective study	304	Head, chest, abdomen, limbs	12 (data known for 28 subjects)	N/A	N/A	Clinical and instrumental
Tenenbaum et al. [108]	2017	Retrospective study	360	Chest, limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Osterberg et al. [109]	2017	Retrospective study	48	Abdomen, limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Ramos et al. [110]	2017	Retrospective study	3894	Abdomen	N/A	N/A	Non-fatal	Clinical and instrumental
Orsi et al. [111]	2017	Retrospective study	4770	Head, limbs	N/A	N/A	Non-fatal: 4726 Fatal: 44	Clinical and instrumental
Sathish et al. [112]	2018	Case report	1	Head	N/A	Fallen on his own	Fatal	Autopsy
Le Bian et al. [113]	2018	Case report	1	Abdomen, limbs	N/A	Collision with a motor vehicle	Non-fatal	Clinical and instrumental
Otsby et al. [114]	2018	Case report	1	Head, neck	1	N/A	Non-fatal	Clinical and instrumental

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Table 1 (continued)

Author	Year	Study type	Cases	Injury location	Helmet use	Type of dynamics	Mortality	Method of injuries evaluation
O'Hern et al. [115]	2018	Retrospective study	236	Head, neck, chest, abdomen	146	Collision with motor vehicle: 181	Fatal	Clinical and instrumental
Thompson et al. [116]	2019	Case report	1	Abdomen	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Abdelrahman et al. [2]	2019	Prospective study	150	Head, neck, chest, abdomen, limbs	4	Collision with motor vehicle: 129	Non-fatal: 145 Fatal: 5	Clinical and instrumental
Cheong et al. [117]	2020	Retrospective study	157	Head, chest, abdomen, limbs	N/A	N/A	Non-fatal: 142 Fatal: 15	Clinical and instrumental
Sundet et al. [118]	2020	Retrospective study	225	Head	N/A	N/A	N/A	Clinical and instrumental
Medina et al. [119]	2020	Retrospective study	41	Head, neck, chest, abdomen	N/A	N/A	Non-fatal	Clinical and instrumental
Takeda et al. [120]	2020	Prospective study	25	Head, neck, chest, abdomen, limbs	0	Collision with motor vehicle: 25	Non-fatal	Clinical and instrumental
Baschera et al. [121]	2021	Retrospective study	1019	Head	113	N/A	Non-fatal: 94 Fatal: 19	Clinical and instrumental
Taha et al. [122]	2021	Case report	1	Neck, limbs	N/A	Collision with a motor vehicle	Non-fatal	Clinical and instrumental
Kleinertz et al. [123]	2021	Retrospective study	435	Head, abdomen, limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Matuzalem et al. [124]	2021	Retrospective study	125	Head, chest, abdomen, limbs	97	N/A	Fatal	Clinical and instrumental
Sarfati et al. [125]	2022	Case report	2	Abdomen	N/A	Fallen on his own	Non-fatal	Clinical and instrumental
Rao et al. [126]	2022	Case report	4	Abdomen	N/A	N/A	Non-fatal	Clinical and instrumental
Indiaminov et al. [127]	2022	Retrospective study	17	Head, chest, abdomen, limbs	N/A	N/A	N/A	Clinical and instrumental
Kent et al. [128]	2022	Retrospective study	387	Head, neck, limbs	N/A	N/A	Fatal	Clinical and instrumental
Døving et al. [129]	2022	Retrospective study	62	Head	24	N/A	Non-fatal	Clinical and instrumental
Siang et al. [130]	2022	Retrospective study	27	Neck, chest, abdomen, limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Zhang et al. [131]	2022	Retrospective study	97	Head, neck, chest, abdomen, limbs	N/A	Collision with motor vehicle: 97	Non-fatal	Clinical and instrumental
Rauer et al. [132]	2023	Retrospective study	279	Limbs	N/A	N/A	Non-fatal	Clinical and instrumental
Indiaminov et al. [133]	2023	Retrospective study	151	Head, chest, abdomen, limbs	N/A	N/A	Fatal	Clinical and instrumental

0–14 age group [6,20,29,33]. Moreover, head injuries have been identified as the leading cause of death or long-term disabilities [6,29,64,71,73,94,111].

Our study confirmed that the head was the most injured region in case of bicycle accidents.

Head lesions often result from high-energy collisions between bicycles and motor vehicles [43]. Although rare, head damage leading to fatalities has been observed in cases of low-speed falls from bicycles without collision, particularly when involving a forward fall onto the handlebars [44,95].

In particular, our results evidenced that isolated lesions to the head, without injuries to other part of the body, were observed in 520 cases after falls from the bicycle only, and in 509 subjects after motor vehicle collision [1,5,12,14,36,38,49,50,52,61,66,70,86,91,112]. This finding may be relevant, as lesions to the head and other body regions were mainly reported in high energy traumatic impacts with other motor vehicles (16,618 cases involving other motor vehicles compared to 4062 isolated bicycle falls) [2,4,6,16,26,29,31–33,41,44,46,48,53–55,60,63,64,71,72,78,80,83,84,95,98,99,101,105,115,120,131].

In high-energy fatal collisions, neurogenic shock resulting from head injuries, such as subdural hemorrhage, brain contusions and diffuse axonal damage and intracerebral hematomas, is the primary cause of death [43,49]. These lesions are frequently associated with depressed-comminuted fractures of the cranial vault, predominantly involving the frontal and temporal bones rather than the occipital bone [127]. Most contusions occur at the inferior surface of the frontal lobes and the inferolateral surface of the temporal lobes [49]. Hence, head trauma often occurs in regions that are typically protected by helmets

[63]. In severe trauma, a ring fracture at the base of the skull, resulting from the high impact of the parieto-occipital region against the ground, may be observed [38]. The injury most linked to poor outcomes is subarachnoid hemorrhage, followed by cerebral contusions, acute subdural hematoma, and brain swelling. It has been observed that young individuals are more prone to extradural hematomas, which has been attributed to the stronger adhesion of the dura mater to the skull bone in older individuals. In contrast, elderly people are more likely to present with subdural hematomas, contusions, intracerebral hematomas, and intraventricular bleeding [49]. Most contusions typically occur on the inferior surface of the frontal lobes and the inferolateral surface of the temporal lobes. Evidence from models of the human head suggests that these preferred areas coincide with areas of high shear stress during impact simulations.

Injuries to the facial region encompass eye trauma, facial soft tissue damages, and fractures [43]. Bicycle brake handles can determine transorbital intracranial penetrating lesions. These fatalities may be rapid due to vascular damage, vital brain center involvement or potentially delayed caused by subarachnoid and/or intraventricular hemorrhage, meningitis, or cerebral abscesses. Autopsy findings typically reveal an injury above the upper eyelid with a fractured roof of the orbit [52,112]. The external wound may be minimal without any laceration of the eyeball, yet the cerebral damage can be severe enough to be fatal [70]. In cases of penetration by the bicycle brake handle, the eye globe may be pushed aside with ecchymosis as the only external evidence of trauma [112]. The zygoma is frequently involved in midface fractures, as susceptible to crash from external force [1]. Low-impact trauma commonly observed in bicycle accidents is more often

associated with soft tissue abrasions, hematoma, and dentoalveolar fractures [88]. Severe accidents, even in helmeted cyclists, can result in mandibular fractures as conventional helmets offer limited protection to the lower part of the face. The most common fracture sites are the mandibular body, followed by the condyle [129].

4.2. Neck injuries

Spinal injuries in cyclists predominantly occur at the level of the cervical spine. These lesions often involve fractures and dislocations, primarily between the first and second cervical vertebrae or cervico-occipital articulation, resulting in separation or contusion of the spinal cord [127]. Bicycles provide limited protection to the cervical spine during accidents, and conventional bicycle helmets do not offer specific advantages over motorcycle ones in safeguarding this area [119].

In the data we analysed, spinal lesions were the least frequent, but always associated with other injuries, especially at the head, and related to high energy accidents involving other vehicles [2,15,16,20,24,25,31,32,37,45,53,58,63,68,73,78,80,83,85,92,96,101,105,106,114,115,119,120,122,128,130,131].

In cases of high-energy trauma, helmet buckles may cause injuries to the neck cartilages. The most common fractures involve the superior horn of the thyroid cartilage, followed by the greater horn of the hyoid bone [122]. These ruptures occur when the helmet buckle is located over the larynx during accidents, forcing the cartilage to flex during head and neck impact [114].

The helmet strap may compress the soft tissues of the neck potentially hurting the vertebral artery. This is typical of low-speed accidents, where individuals are initially asymptomatic, but after hours or days they may complain discomfort, likely accompanied by neurological symptoms such as nausea and vomiting, which may progress to coma and fatality. Traumatic dissection of the vertebral artery can lead to cerebral infarction, followed by brainstem compression and edema. The vertebral artery is particularly vulnerable to longitudinal stretch, especially after sudden neck movements like hyperextension and/or rotation. Therefore, in cases of delayed symptoms, vertebral artery dissection should be sought in autopsy as a potential cause of death [83, 134].

4.3. Thoracic and abdominal injuries

These lesions are observed in fatal crashes involving heavy vehicles [6,117]. Bilateral rib fractures primarily affect the upper ribs, specifically the first to the sixth, along the midclavicular and anterior axillary lines [127]. These injuries may occur in conjunction with pneumothorax, pulmonary contusions, and haemothorax [93]. Isolated visceral abdominal trauma is infrequent and mainly involves lacerations or haematomas of parenchymatous organs, such as spleen, liver, or kidneys [48,127].

In our study, thoracic and abdominal lesions were less frequent than the head and limbs, but more common than the neck. Thoracic injuries were never reported isolated, but always combined with other body lesions, and mostly a result of high energy trauma with other vehicles [2, 4,6,19,31,32,44,48,53,55,63,71,72,78,99,101,105,106,115,120,131]. Similarly, abdominal injuries presented the same co-occurrence, except the handlebars traumatic impact on the abdomen, in which in most of the cases the dynamics involved the autonomous fall of the rider. Pediatric subjects were the most affected individual with frequent fatal outcome [22,27,35,40,42,47,56,57,67,74,82,87,100,102,110,116,125, 126].

Bicycle handlebars may cause blunt trauma to the abdominal viscera, especially in children, whose abdominal musculature is less developed than adults. During the impact, the handlebars act as a spear, concentrating energy into a focal point in the abdomen, forcefully compressing the relatively immobile abdominal organs between the handlebars end and the vertebral bodies [56]. Externally, a bruise made by the

handlebar edge on the abdominal wall is usually detectable. In cases of low-energy trauma, handlebar pressure may only result in a traumatic hernia of the abdominal wall or a direct inguinal hernia without associated intra-abdominal lesions [47,110]. In severe trauma, depending on the impact point of the handlebar, damages to internal organs, both intraperitoneal (such as the liver, spleen, and intestines) and retroperitoneal (such as the pancreas and kidneys), can be observed [42,57,87, 100,102,126]. Even the laceration of the abdominal aorta, with hemoperitoneum and retroperitoneal hemorrhage, may occur [22].

4.4. Limb injuries

These are the most frequent casualties in bicycle accidents, after the head, and fractures represent the most common lesion for both upper and lower limbs [41,43,76,111].

Our study confirmed these findings, and limb injuries were often associated with other body lesions, especially the head, in particular in motor vehicle accidents [2,6,11,15,19,24,26,28–33,41,43,46,53–55,58, 60,62–65,68,71,76–79,84,85,89,90,92–96,98,99,105–109,111,113, 117,119,120,122–124,127,128,130,131,133]. In few cases, isolated limb injuries were rarely reported with no fatal events, and dynamics, when present, always involved the autonomous fall of the rider [59,75, 97,103,104].

Fractures of the upper limbs are more common than the lower limbs and primarily affect adults and the elderly [71,79,123]. Forward falls typically cause upper limb fractures due to an impact between the body and the road surface [127]. The clavicle and radius are the most injured bones [41,53,71,93]. Clavicle rupture usually occurs after front-end falls with direct blow to the shoulder and are often associated with concussions and rib fractures. Radial head brakeages commonly result from falls on an outstretched hand [93, [Goldstein, 2016]. Non-fracture lesions predominantly involve the shoulder caused by traction injuries and hyperabduction of the arm [53,104].

Lower extremity fractures are less common and usually occur during car crashes or severe trauma when the body impacts the vehicle or the ground in sideways falls [44,77].

Pelvis and hip fractures are typically nondisplaced and their incidence increases with age [79,93]. Femur fractures are usually severe, involving dislocation and tearing of the skin [93,117]. Leg fractures often affect the tibia and fibula and are commonly associated with lateral car collisions. The severity of leg injuries is dependent on the speed, the height of the bicycle seat and the height and length of the car hood [131]. Regarding non-fracture lesions of the lower limb, handlebar injuries may involve the common femoral artery, which can be easily torn in blunt trauma, as it is anatomically immobile [125].

4.5. Injuries assessment in forensic evaluation of the bicycle accident

Forensic evaluation of road casualties involving bicycle riders must investigate their injuries to find out how they have been caused and the underlying accident dynamics. Accident reconstruction can be extremely difficult due to the complexity of the elements to consider. This may require interviewing individuals or eyewitnesses, setting up mechanical or engineering investigations, and acquiring digital images of the accident, especially security cameras, or camera worn on the rider's helmet, or from the dashboard of the vehicles involved [135].

Our study demonstrated that injuries in bicycle riders can be the result of autonomous falls, being at low energy impact, or motor vehicle crash, defined as high energy collision. The former usually produces isolated lesions to the head or limbs caused by the impact on the ground, or to the abdomen through the handlebar compression, especially in the pediatric population. The latter, due to motor vehicle involvement, tends to damage more body regions, especially thorax and abdomen.

The use of helmet may significantly reduce head injuries, in riders of every age, and in any kind of accident [6,111]. In our review, the use of helmet was reported only if the head was injured, but not in all cases.

However, in cases with head injuries, the helmet was worn in only 22 % of subjects, while in case of neck injuries it was worn in 10 % of the cases. Helmets have been demonstrated to be effective in dispersing the energy between the head and the impacting object, but the head is not completely covered, especially the temporal bones, which are thin and exposed to fractures, easily leading to tearing of the medial meningeal artery and then extradural hematomas [49,115]. Besides, most of the current bicycle helmets do not properly protect the face [Baker 2023]. Despite these limitations, helmets have been proved to be effective in preventing skull fractures, brain injury, diffuse axonal damage, and subdural hematoma, as reported in the experimental study carried out by Wang et al. [136]. In the meta-analysis by Høy et al., it is reported that helmets decrease head injuries by 48 %, increasing up to 60 % in case of severe cranial damage and 71 % in fatal events. Traumatic brain damage may be reduced up to 53 %. Moreover, the protective effect of the helmets has been found to be higher in single collisions compared to crashes with other vehicles, as in the latter cases injuries are more severe due to high energy impacts [137,138].

The examination of the helmet, especially in on-site inspection, may provide useful information in reconstructing the accident dynamics. The severity and the characteristics of the impact (angle of collision, rotational acceleration sustained, and head speed) may be extrapolated through the helmet conditions [139,140].

Our study also evidenced that thoraco-abdominal lesions were mostly caused by high energy impacts with other vehicles. These injuries tend to be fatal because of internal organ lacerations and subsequent hemorrhagic shock. The lack of helmet associated with severe trauma usually ends up in fatal outcomes and post-mortem examination frequently reveals depressed-comminuted fractures of the cranial vault and multiple rib fractures [93,127].

Isolated abdominal lesions can be related to accidental autonomous falls and handlebar pressure. Despite the low energy involved, fatal outcomes may occur because of internal organ damage, especially splenic or hepatic lacerations [42,57,87,100,102,126]. In such cases, autopsy should include a search for bruising patterns that mimic the shape of handlebar components on the external surface. Prevention systems have been suggested such as handlebars made of soft materials [27] or retractable prototypes composed of a spring–mass–damper unit, that in case of compression, retracts and discharge the force exerted on the abdomen [141].

Lastly, in our study, limb injuries were usually associated with lesions in other body parts, especially in high energy trauma, when other vehicles were involved. Instead, limbs were more damaged in isolated bike rider falls and never associated with death. In particular, upper limb fractures typically result from forward falls due to impact with the road surface [127]. Conversely, lower extremity fractures occur in lateral car collisions, where the body is hit by motor vehicles [44,77, 131]. A distinct distribution of limb fracture locations was observed based on the age of the cyclist. Younger cyclists have a greater risk of lower extremity fractures, especially to the femur. In contrast, older cyclists have an elevated risk of sustaining fractures to the upper extremity and pelvis. The increased incidence of pelvic fractures can be attributed to the susceptibility of these bones to osteoporotic changes and is associated with a higher mortality rate [79,115].

5. Conclusion

This review highlights that lesion distribution is fundamental in reconstructing accident dynamics, especially if related to an isolated fall or to the involvement of other vehicles. The systematic assessment of injuries offers valuable insights that must be integrated with circumstantial and engineering data, in addition to whether the victim worn the helmet or not, as unprotected head is prone to more severe injuries, especially in low energy trauma. On the other hand, impact points on the helmet may help accident reconstruction. The use or not of helmet can be relevant in riders who use the bicycle for work, as accidents can easily

turn into insurance claims. Data analysis revealed that the more the accident was severe, the more widespread injuries were sustained due to motor vehicle impact and high energy trauma. Therefore, resources should be invested in adequate bicycle infrastructure combined with driver responsiveness of cyclists on the road.

Further studies should also include electric bikes and their dynamics, as they can reach high speed and potential high-energy impacts.

CRediT authorship contribution statement

Elena Giovannini: Conceptualization, Data curation, Formal analysis, Investigation, Methodology. **Susi Pelotti:** Supervision. **Mattia Innocenti:** Data curation. **Paolo Fais:** Supervision. **Simone Santelli:** Data curation. **Maria Paola Bonasoni:** Data curation, Formal analysis. **Guido Pelletti:** Supervision.

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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