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Pediatric and adolescent injury in mountain biking

Dennis J. Caine[a], Kasey Young[a] and Aaron J. Provance[b]

[a]Department of Kinesiology and Public Health Education, University of North Dakota, Grand Forks, ND, USA; [b]Department of Orthopedics, University of Colorado School of Medicine, Aurora, CO, USA

ABSTRACT

Mountain-biking has become a popular competitive and recreational activity but also involves risk of injury. This article provides an overview of what is known about the scope of the injury problem affecting children and adolescent mountain bikers, the risk factors involved and injury prevention strategies. The proportion of injured child and adolescent mountain bikers ranges from 10.6% to 64.0%, but few studies provide separate analysis of youth injuries. Upper extremity injuries appear most common except among adolescents where the risk of head injury and traumatic brain injuries are greater. Concern is raised regarding the reported frequency of spine fractures and spinal cord injuries. Multi-faceted, longitudinal injury research focusing on youth mountain bikers is required to provide a reliable basis for testing risk factors and evaluating preventive measures. Reducing mountain biking-related injuries will require multiple strategies that integrate approaches from education, engineering, and evidence-based safety measures and their enforcement.

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Mountain biking; off-road cycling; children; adolescent; injury; epidemiology

Introduction

Mountain biking (MTB) is the sport of riding bicycles off-road, often over rough terrain, using specially designed mountain bikes. The members of the Velo Club Mount Tamalpais in California generally receive the credit for establishing MTB as a sport. They invented the Repack Downhill race, held regularly between 1976 and 1979 just across the famous Golden Gate Bridge from San Francisco (https://www.olympic.org/cycling-mountain-bike#). MTB has grown significantly from its inception and is now a popular recreational and competitive activity for individuals of all ages (Ashwell, McKay, Brubacher, & Gareau, 2012). In the United States, the number of mountain bikers increased from 6.89 million in 2007 to 8.61 million in 2016 (Outdoor Foundation, 2016).

MTB can be subdivided into cross-country (recreational and competitive), trail (recreational), enduro (recreational and competitive), and downhill (recreational and competitive). Cross-country MTB consists of riding short travel suspension, lightweight bicycles on rolling terrain, uphill, and downhill with various mild-moderate technical sections along the ride or race. Races vary in length from short track (~15–20 miles) to long endurance races (~50–100 miles). Trail MTB consists of slightly heavier bikes with medium travel suspension and a focus on more adventurous, technical sections of

CONTACT Dennis J. Caine dennis.caine@und.edu

trail. Enduro and downhill disciplines are similar as they focus on the downhill aspect of the sport with long travel suspension, heavier bikes. Enduro races consist of timed downhill sections and untimed uphill sections of the course. Downhill MTB typically occurs on mountain bike terrain parks (MTBTP) within ski areas, often consisting of man-made terrain futures, which increase size of jumps and drops as well as banked turns to maintain high rates of speed through more technical sections of trail. MTBTPs often include chair lift access, where riders are transported up the slope, and then bicycle downhill.

Summertime use of chairlifts at ski resorts allow recreational and competitive mountain bikers as young as 6 years of age to gain access to steeper, longer and more technical terrain, including larger jumps and drops as well as steeper and rougher descents (Ashwell et al., 2012; Romanow, Hagel, Nguyen, Embree, & Rowe, 2014). In North America, there are more than 50 Ski Resorts that offer lift-accessed mountain-biking trails, with more scheduled for development (Lift Accessed Mountain Biking, Wikipedia). These parks are open to the public and all skill levels. Whistler Blackcomb Mountain Bike Park in British Columbia, for example, has three lifts that offer access to 45 trails with more than 155 miles and 3,800 vertical feet of riding. (http://www.whistlerbike.com/index.htm).

Mass media showcasing MTB and the inclusion of this sport in the Olympics are helping to drive its popularity among youth. MTB attracted almost two million (1,975,000) youth participants in the United States, ages 6–17 years in 2016, an increase of 200,000 participants since 2007 (Outdoor Foundation, 2016). Among children and adolescents, physical activity can improve bone health and cardiorespiratory and muscular fitness, decrease levels of body fat, reduce symptoms of depression, and improve cognitive skills and ability to concentrate and pay attention (Raspberry et al., 2011; U.S. Department of Health and Human Services, 2008). However, engaging in mountain biking at a young age involves exposure to variable and often unpredictable environmental conditions that may be associated with risk of injury.

Young mountain bikers may be particularly vulnerable to injury due to such growth-related factors as the adolescent growth spurt, susceptibility to growth plate injury, differences in maturity status, proportionately large trunk and head and short legs (children), and, relative to adults, longer recovery and differing physiological response after concussion, and slower acclimatization to extreme weather conditions (Caine & Purcell, 2016). They might also be at risk because of decreased neuromuscular control, strength, emotional maturity, and judgment compared with adults (National Center for Injury Prevention and Control, 2009-2018). The unusual and sometimes risky physical demands of MTB may create conditions under which these potential risk factors can more readily exert their influence.

The increased involvement of children and adolescents in MTB from an early age and continued through the years of growth, against a background of their unique vulnerability to injury, gives rise to concern about the risk and severity of injury in this sport. In the United States, an estimated 217,433 patients, ages 8–97 years, were treated for mountain-bike related injuries in US emergency departments during 1994–2007 (Nelson & McKenzie, 2011). Patients aged 14–19 years sustained a greater proportion of traumatic brain injuries than did patients aged 8–13 years and ≥ 20 years combined. In Canada, during 1995–2007, 17% of all mountain bikerstreated at a provincial spine

referral center for spinal column and spinal cord injuries, were aged 14–20 years (Dodwell et al., 2010).

In addition to the immediate healthcare costs, pediatric and adolescent MTB injuries, particularly head and spine injuries, may have long-term consequences, resulting in reduced levels of physical activity and, therefore, a reduction in wellness. The medical, personal, and societal costs of these injuries are great. The purpose of this review is to illuminate the incidence and nature of injury affecting pediatric and adolescent mountain bikers, and what is known about risk factors and preventive measures, with the hope of generating understanding and further research.

Search procedures

The primary reference sources for this study were the electronic database SCOPUS, the world's largest database of peer-reviewed coverage of Medline, SPORT Discus, and CINAHL. The literature search was limited to published, peer-reviewed reports and involved the following search terms as well as extensive cross-referencing: mountain biking, injury, injury risk factors, and injury prevention. Only studies published in English and that incorporated data related to child and adolescent mountain bike injuries were included. Studies which did not report age of patients/participants were excluded. Published studies arising from descriptive and analytical studies (including case series, cross-sectional, cohort, and case-control designs) related to mountain biking injuries were reviewed by two reviewers for possible inclusion.

Methodological limitations

In reviewing the existing literature, several methodological limitations arose as follows:

- Most studies present case data of MTB injuries sustained while riding on mountain bike trails, commercial mountain bike parks or other off-road trails treated at hospital emergency departments and mountain-based medical centers.
- No original studies dealing specifically with child/adolescent mountain bikers are reported in the literature.
- Few studies performed age specific analyses, thus information on the epidemiology of injury in mountain biking is largely reflective of all ages.
- Definition of injury varies considerably across studies, from mountain bike injuries that were treated in hospitals and clinics, or those severe enough to prevent a rider from finishing a race, to any injury incurred while riding an off-road bicycle.
- Diversity of study populations with respect to age, technique level, and type of environment, and including recreational and competitive mountain bikers.
- Lack of uniformity in reporting anatomical location, type, and severity of injury across studies.

In spite of these limitations, the intent of this article was to find the best answers possible by presenting the various properties and findings of the studies in an integrative way and to provide a global picture of mountain bike injuries. Findings generally

represent a broad spectrum of ages, including children and adolescents. However, when possible data pertaining to pediatric and adolescent MTB injuries are highlighted.

Who is affected by injury?

Overall rates

Twenty-one published studies on injuries sustained during MTB, including data on children and adolescents, are summarized in Table 1. Perusal of this table reveals an extant literature that includes both competitive and recreational mountain and off-road cyclists. The studies reviewed provide aggregate data on a wide age range (5–97 y) of injured male and female mountain bikers with few specifics regarding age-specific data on incidence and distribution of injury. Most cases are male (Range: 57–88%), and most of these are young adult males, reflecting the popularity of this sport in this age/gender group. The proportion of injured child and adolescent mountain bikers in these studies ranges from 10.6% to 64.0%, indicating that children and adolescents are well represented among these reports of injured mountain bikers.

Two studies, in particular, report a relatively high proportion of injured children and adolescent mountain bikers. Romanow et al. (2014) reported that the majority of injured mountain bikers in their study who were hospitalized (i.e., cases) or discharged (controls) were children and adolescents (83.9% and 89.9%, respectively). Similarly, Jeys, Cribb, Toms and Hay (2001) reported that the largest group of rural England mountain biking patients in their study were aged 8–15 years (41.7%), including one 11-year old mountain biker who had a significant head injury requiring helicopter transfer to the regional neurosurgical center.

Few studies report injury rates for MTB participants. Among recreational mountain bikers, ages 10–58 years, one study reported a rate of 1.54 injuries per 1000 biker exposures incurred at the Glentress MTB Center in Scotland (Aitken, Biant, & Court-Brown, 2011). Nelson and McKenzie (2011) reported an annual overall rate of 6.2 per 100,000 US population, including competitive and recreational mountain bikers ages 8-97 years. In contrast, Kim et al. (2006) reported a rate of 6.7 per 100,000 for MTB riders, ages 2–70 years, on mountain bike trails or commercial mountain bike parks in British Columbia. A common finding in these studies was that the majority of injuries occurred in patients engaged in sport for recreational rather than competitive purposes.

Becker et al. (2013) reported an overall (training and competition) injury rate of 16.8 injuries/1000 hours exposure for downhill mountain bikers ages 14–53 years, with 31% requiring medical attention. Using a more stringent definition of injury, Gaulrapp, Weber, and Rosemeyer (2001) reported a rate of 1 injury/1000 hours of competing or training for off-road bicyclists ages 8–80 years. Becker et al. (2013) found that compared with professional riders (13.0 injuries per 1000 hours exposure), experts (17.9 injuries per 1000 hours exposure) were at significantly higher risk of getting injured (OR 1.34; 95% CI, 1.02 – 1.75; $p = 0.03$).

Table 1. Injury rates among mountain bikers.

Study	Design	Study Period	Subjects	Age/Proportion of Patients ≤ 18 y	Injury Definition	Injury Rate
Kotlyar 2016	Retrospective Chart Review	June 2012 through June 2015	304 mountain and road cyclists; 70% M and 30% F.	bimodal age distribution <11 to >70; 86 cases ≤ 20 y. (28.3%)	Cases presenting to a rural mountain resort-based medical center. Patients injured while riding on road (road injuries) or trail (trail, dirt, or gravel) injuries.	The majority of injuries (67%) occurred while trail riding
Romanow et al., 2014	Case-control	May 2008 to October 2010.	31 hospitalized mountain bikers (cases); 83.9% M and 16.1% F 378 controls; 89.9% M and 10.1% F; 31 cases, including 26M and 5F; 378 controls, including 340M and 28F	74.2% of cases were ≤ 18 years of age; 82.3% of controls were ≤ 18 years of age	Cases were hospitalized recreational bicyclists injured in MTBTPs and presenting to one of 7 EDs. Controls were bicyclists injured in MTBTPs who were discharged from one of 7 EDs.	A total of 465 injuries were sustained: 36 injuries in the case group and 429 in the control group
Becker et al., 2013	Prospective survey (questionnaire)	April-September, 2011	249 downhill riders	mean age 23.5 ± 6.8 y; age range 14–53 y	Any injury resulting from training or competition, irrespective of medical treatment requirement or time loss from sports activities	16.8 injuries per 1000 h of exposure (training and competition)
Bush et al., 2013	Case series (prospective survey of ER cases)	12 months	765 ER visits from recreational mountain bikers	average age was 29.3 y, age range = 16–64y	Patients presenting to one of two emergency departments who sustained an injury while participating in recreational mountain biking	A total of 1,079 injuries with 511 involving the upper extremity, including 114 hand injuries and 103 wrist injuries (occurring in 207 patients)
Ashwell et al., 2012	Case series (retrospective chart review)	16 May 2009 to 12 October 2009	898 injured mountain bikers	age range 7–66 y, median age 26 y; 86% male and 14% female	Injuries incurred while riding in the bike park and presented to the Whistler Health Clinic	1759 injury diagnoses in 898 subjects. Two children, ages 12 and 10 y were transferred by helicopter to a children's trauma center
Nelson and McKenzie (2011)	Retrospective analysis of mountain bike-related injuries treated in US EDs (NEISS)	1994 to 2007	An estimated 217,443 patients treated for an average of 15,531 injuries per year. 80.8% were boys or men	Mean age 29.8 ± 13.3 years (Range, 8–97 years).	To be included the patient must have been operating a mountain bike at the time of injury	Annual overall injury rate of 6.2 per 100,000 population.
Aitken et al., 2011	Prospective	1 July 2007 to June 30th, 2008	202 injured mountain bikers; 88% M (11–58 y) and 12% F (10–49 y)	age range 10–58 y; 31/202 (15%) injured mountain bikers were < 20 years of age	Recreational mountain bikers seeking medical care at one of five medical facilities	Injury rate was 1.54 injuries per 1000 biker exposures

(*Continued*)

Table 1. (Continued).

Study	Design	Study Period	Subjects	Age/Proportion of Patients ≤ 18 y	Injury Definition	Injury Rate
Dodwell et al., 2010	Case series	Patients who were injured during mountain biking seen at a Provincial spine refer center between 1995–2007	107 subjects, including 102 M and 5F	mean age 32.7 years; age range 14–70 years; 17.5% of patients were 14–20 years of age	Patients who were injured during mountain biking, and who were seen at a provincial spine referral center. All but 2 subjects were recreational mountain bikers	Mean risk = 0.20 per 100,000 British Columbia residents. 79 patients (73.8%) sustained cervical injuries, and 28 patients (24.2%) sustained thoracic or lumbar injuries.
Müller et al., 2008	Cross-sectional: retrospective (interview)	Participants of international mountain bike competitions in Switzerland	473 male competitive mountain bikers	Average age = 30.8 y (age range = 9–66 y); 50/473 (10.6%) riders were junior riders (12–18 y)	History of injury and dental injuries sustained while mountain biking	251/473 (53.1%) had experienced injuries. Juniors experienced more dental injuries (10%) than amateurs or professionals
Kim et al., 2006	Retrospective case series	Trauma registries and patient charts for 3 trauma centers from 1992–2002	399 patients; young males (ages 21–30) was the most commonly injured age group.	ages 2–70 years; The youngest patient, a passenger, was 2 y and the younger rider was 5 y.	Injuries that occurred while engaging in a recreational bike riding activity that took place in mountain biking trails or commercial mountain bike parks.	399 patients sustained 1,092 injuries. There was a 3-fold increase over 10 y in incidence from 2 per 100,000 population to 6.7 per 100,000 population
Bentley et al., 2006	Insurance Claims (retrospective chart review) of adventure activities related to injury	4 July 2004 to June 2005	18, 697 adventure tourism and adventure sports injury claims.	13% of all claims involved the 16 to 20-y old age group		2618 mountain biking claims accounted for 14% of all injury claims (second to horse riding) for a rate of 14.8 per 1000 participants
Chow and Kronisch (2002)	Prospective (Interview)	7 off-road competitive events during summers 1994–98	97 injured mountain bikers; male (74.2%) and female (25.8%)	Mean age = 28.3. Range 15–59 y.	All competitive riders who sustained an injury severe enough to prevent them from continuing their respective race	97 riders sustained 190 injuries
Kronisch et al., 2002	Prospective (Interview)	Annual mountain bike competitions (1994–2001)	20,769 participants (86% M; 14%F)	71M mean age 28.4; range 15–59 y) and 22 F (mean age 30.8; range 22–52 y) were injured	An injury must have occurred during competition and was severe enough to prevent the rider from finishing the race	71 M and 22 F were injured. Overall injury rate was 0.77% (22/2,869 starts) for women vs. 0.40% (71/17,900 starts) for males
Gaulrapp et al., 2001	Cross-sectional (questionnaire)	Off-road bicyclists subscribing to a popular mountain bike magazine	3873 cyclists returned questionnaires (77.5%)	mean age 25; ages from 8 to 80 years.	An injury was defined as one preventing the athlete from at least 1 day of mountain-biking.	8133 injuries reported by 3474 athletes (89.7%); 1 injury per 1000 h of biking
Jeys et al., 2001	Prospective case series (orthopedic trauma unit)	12 months; recreational or competitive off-road mountain biking	84 patients; 70 M (83%) and 14F (17%).	mean age 22.5 years; range 8–71 years; 35/84 (41.7%) patients were aged 8–15 y.	All injuries caused by off road mountain cycling (mostly recreational) referred to the Royal Hospital.	133 injuries, ranging from 1–6 injuries per patient

(*Continued*)

Table 1. (Continued).

Study	Design	Study Period	Subjects	Age/Proportion of Patients ≤ 18 y	Injury Definition	Injury Rate
Rivara, Thompson, Thompson, & Rebolledo, 1997	Prospective (case series)	Prospective study of 7 EDs from March 1992 through August 1994 (follow-up questionnaires; 88% response rate)	Total of 390 injured bicyclists, including 127 "off-road cyclists." Off-road cyclists were 86.6% M and 13.4% F.	18.8% of off-road cyclists were 6–19 y of age.	Any patient who was injured while on a bicycle and presented to an ER	Off-road cyclists were about half as likely to sustain head and face injuries.
Kronisch et al., 1996a	Prospective (pilot study)	NORBA downhill and cross-country off-road races in May-July 1995	4074 cross-country (85.9% M and 14.1% F); 1920 downhill racers (88.8% M and 11.2% F)	Age group classes are junior (12–18), senior (19–34), veteran (35–44) and master (45 and over)	Injuries were considered reportable if they occurred during competition and prevented the cyclist from competing in the event	Overall injury rates were 0.49% (20/4074 starts) and 0.37 injured cyclists per 100 h racing for CC; 0.51% (11/2158 starts) and 4.34 injured cyclists/100 h for the DH event ($p = 0.01$)
Kronisch et al., 1996b	Prospective (pilot study)	Off-road bicycling race, July 6–10, 1994	3624 cyclists in all events with some cyclists participating in multiple events	age range 16–39 years	Any episode of acute trauma sustained during competition that required medical attention and rendered the rider unable to compete in the event	16 cyclists had 44 injuries/4027 starts
Gassner, Tuli, et al., 1999	Case series (hospital data)	Oral and maxillofacial trauma patients during 1991–96	502 bicyclists with 57.6% M and 42.4% F; 60 mountain bikers with 78.3%%M and 21.7%F	Bicyclists mean age 24.5 y and age range 10–80 y; Mountain bikers mean age 30.7 y and age range 10-60 y.	Evaluate different patterns of oral and maxiollofacial trauma in bicycle and mountainbike accidents.	Mountain bikers sustained more severe oral and maxillofacial trauma
Kronisch & Rubin, 1994	Retrospective survey	Off-road bicycling organizations	Of 426 mailed surveys, 265 were completed and returned (62.4%); subjects 75.5% M and 24.5% F	Subjects ranged in age from 10–56 years	Cyclist sought medical attention for an injury and was unable to ride for ≥1 day due to injury. (n = 60 injuries)	Of 265 participants, 85.7% reported injuries sustained while mountain-biking during the last 12 months.
Chow et al., 1993	Retrospective survey	Off-road bicycling organizations	Of 459 mailed surveys, 268 (58.4%) were returned; 82.8% M and 17.2% F	mean age 36.2 y; age range 14–68 y.	Injury sustained while riding all-terrain bicycles during previous year.	225 of 268 subjects (84%) had been injured while riding all-terrain bicycles

Events

As might be expected, downhill MTB is associated with a greater risk of injury than other forms of mountain biking due most likely to the relatively high velocities, jumps and trails with obstacles to avoid (Becker et al., 2013). Based on their study of three major off-road bicycle races in 1995, Kronisch, Pfeiffer, and Chow (1996a) reported a significantly higher rate of injury in the downhill (4.34 injured cyclists/100 h) than in the cross-country (0.37 injured cyclists/100 h ($p = 0.01$) events. In a study of a major off-road bicycling race the previous year, Kronisch, Chow, Simon, and Wong (1996b) reported variable injury rates by event with eliminator having the highest rate (2.17 injuries per 100 starts), following by cross-country (0.55 per 100 starts), downhill 0.32 per 100 starts), and dual slalom (0.15 per 100 starts).

Where does injury occur?

Anatomical location

Studies reporting aggregate data on anatomical location of injuries for all ages studied are summarized in Table 2. Comparison of injury distribution by body region shows that upper extremity (UE) injuries are most common (26.9–74.2%) followed by lower extremity (LE) (5.9% to 38.8%) then head/neck/face (HNF) (6.4% to 29.4%). Notably, in a study which involved a majority of children and adolescents, HNF injuries were more frequent (22.1%) than LE (14.6%) injuries (Romanow et al., 2014). Several studies indicate that injured mountain bikers often present with injuries at more than one site (Aitken et al., 2011; Ashwell et al., 2012; Romanow et al., 2014) which is not surprising given the speed and terrain factors.

Some research suggests variation in distribution of injury anatomical location by age and gender. In one study (Nelson & McKenzie, 2011), patients aged 8–13 years sustained a greater proportion of UE injuries than patients aged ≥14 years, and patients aged 14–19 years sustained a greater proportion of head injuries than did patients 8 to 13 years and >20 years combined (IPR, 2.0;95% CI, 1.6–2.5). Nelson and McKenzie (2011) also found that boys and men (21.5%) sustained a greater proportion of shoulder injuries than did girls and women (11.5%), whereas girls and women (23.4%) sustained a greater proportion of LE injuries than did boys and men (18.7%) (IPR, 1.9; 95% CI, 1.6–2.3; IPR, 1.3, 95% CI, 1.0–1.6, respectively).

Environmental location

Competition vs. training

Becker et al. (2013) reported a significantly higher injury rate among downhill riders (OR 1.53;95% CI, 1.16–2.01; $p = 0.01$) during competition (20.0 per 1000 h) than during practice (13.0 per 1000 h). Several earlier studies reported that mountain bike races pose up to a fourfold increased risk of injury (Kronisch et al., 1996b; Kronisch & Rubin, 1994). Since the trails for competition and practice are mostly the same, the increased injury rate during competition may perhaps be explained by psychosocial factors such as altered risk-taking behaviors and life stress.

Table 2. Anatomical location of injury.

Anatomic Region/Study	Kotlyar, 2016	Romanow et al., 2014	Nelson and McKenzie (2011)	Aitken et al., 2011	Ashwell et al., 2012	Kim et al., 2006	Chow & Kronisch, 2002	Gaulrapp et al., 2001	Rivara et al., 1997	Chow et al., 1993
Head/Neck/Face		*98 (22.1%)*		*55 (19.8%)*	*31 (6.4%)*	*255 (23.5%)*	*39 (20.5)*	*(9.1%)*	*34 (19.2%)*	*34 (7.8%)*
Head/Face	12(6)				8 (1.2%)	244 (22.4%)			30 (16.9%)	
Neck/Cervical spine					23 (5.2 %)	11 (1%)	8 (4.22)		16 (9.0%)	
Trunk/Spine		*38 (8.6%)*		*32 (11.5%)*	*38 (8.5%)*	*215 (35.5%)*	*17 (8.9)*	*(6.3)*	*17 (9.6%)*	*103 (23.0%)*
Clavicula										
Ribs	17 (6)				32 (7.2%)		4 (2.1)			
Abdomen	2(1)					59 (5.4%)				
Pelvis					6 (1.3%)	25 (2.2%)				
Upper back										
Lower back										
Upper Extremity	*56 (28%)*	*263 (59.2%)*	*26.9%*	*126 (45.3%)*	*330 (74.2%)*		*65 (34.2)*	*(45.8)*	*72 (40.7%)*	
Shoulder					122 (27.4%)					
Upper arm					12 (2.7%)					
Elbow					37 (21.8%)					
Forearm					8 (1.8%)					
Wrist					109 (24.5%)					
Hand					42 (9.4%)					
Lower extremity		*65 (14.6%)*	*19.6%*	*65 (23.4%)*	*48 (10.8%)*		*69 (36.3)*	*(38.8)*	*54 (30.5%)*	
Hip					4 (0.9%)					
Thigh					1 (0.2%)					
Knee					4 (0.9%)					
Lower leg					1 (.02%)					
Ankle					25 (5.6%)					
Foot					13 (2.9%)					
Other		1 (2.9%								
Total # Injuries	247	34		278	447	1,092	190	8130	177	437

Terrain

The downhill portions of MTB or cross-country (XC) courses are also associated with a higher risk of injury (Bush, Meredith and Demsey, 2013; Kronisch, Pfeiffer, Chow, & Hummel, 2002). Kronisch et al. (2002) reported that the majority of mountain biking injuries occurred to racers while riding downhill, and that 79.2% of cyclists injured in the XC race were injured on the downhill portion of the race course. All fractures and 90.9% of the concussions were sustained during the downhill riding. Similarly, Kronisch et al. (1996b) reported that 13/16 (81.2%) injured cyclists at this race sustained their injuries while going downhill, either in one of the downhill events or on a downhill portion of the XC course.

When does injury occur?

Injury onset

Most injuries reported in studies of mountain bikers are acute injuries. However, this finding may also reflect the short-term, cross-sectional nature of most published studies on this topic. Given the repetitive nature of cycling and the potential for repeated microtrauma caused by vibration or motion, in addition to fatigue, it is not unexpected that overuse injury occurs in this population (Ansari, Nouran, & Khodaee, 2017; Campbell & Lebec, 2015), particularly among competitors. It is estimated that 45–90% of adult mountain bikers experience overuse symptoms (Cambell & Lebec, 2015); however, the extent to which these injuries occur among child and adolescent riders is unknown and awaits further research.

Temporal variations

Time of injury

Ashwell et al. (2012) reported that independent of specific day, clinical arrival times at Whistler Blackcomb Mountain Bike Park peaked in the early afternoon, with 52.3% of all cases registering between 1–4 pm. Clinic visits Saturday and Sunday were the busiest days, accounting for 39.5% of all injuries. Dodwell et al. (2010) reported that 63.6% of mountain bike injuries seen at a provincial spine referral center were seen in the afternoon (12–6 pm), followed by 23.5% in the evening (6–12 pm), and 9.3% in the morning (6–12 am). Ashwell et al. (2012) reported that MTBP clinic visits were distributed over May-October, peaking in August, consistent with the timing of several extreme sporting events, when 35% of all injury cases visited the clinic.

Trends

Nelson et al. (2011) reported a decrease in annual rate of mountain biking injury from 6.9 injuries per 100,000 US population in 1994 to 3.8 injuries per 100,000 in 2007. In contrast, Kim et al. (2006) reported a 3-fold increase in the annual incidence of mountain biking injuries adjusted for 100,000 population (Vancouver regional trauma system) during a 10-year period (1992–2002). The number of patients with severe injuries (AIS > 3 for trunk, spine or head) showed an exponential rise over this same study period. The authors suggested that there were several reasons for this observation including

increased popularity of the sport, steady population growth, and an evolution of style of riding from cross-country to downhill, which carries a higher risk of injury (Kim et al., 2006).

Dodwell et al. (2010) described spine injuries affecting mountain bikers seen at a provincial spine referral center during 1995–2007. Risk of spine injury due to mountain biking was greatest in 2001 and plateaued or dropped off during the subsequent 6 years. The authors speculated this finding may suggest that education, trail marking, riding style modification and protective gear may have some effect on the number of serious mountain biking injuries (Dodwell et al., 2010).

What is the outcome?

Injury type

A summary of data on injury types sustained by mountain bikers, including children and adolescents, is provided in Table 3. A review of the hospital-based studies (Romanow et al., 2014; Ashwell et al., 2012; Nelson & McKenzie, 2011; Jays et al., 2001) shows that the most common injury was fracture (26–45%), followed by concussion (11.2–12.3%). In contrast, the observational studies indicate the three most common injury types as abrasion (38.6–64%), fracture (7–33.3%) and laceration (5.9–17.7%) (Aitken et al., 2011; Becker et al., 2013; Chow & Kronisch, 2002; Kronisch et al., 1996b; Kronisch & Rubin, 1994). However, concussions were also common in these studies, ranging from 5–14.4% of all injuries.

Oral and maxillofacial trauma

Gassner, Tuli, Emshoff & Walsport (1999) reported on injury profiles of 60 mountain bikers seen at the Department of Oral and Maxillofacial Surgery in Innsbruck, Austria between 1991–96. Fourteen of sixty mountain bikers (23.3%) were ≤19 years of age. Records of the injured mountain bikers show 55% with facial bone fractures, 22% dentoalveolar trauma, and 23% soft tissue injuries. In a cross-sectional study of 423 male mountain bikers, including 50 juniors (ages 17–18), 27 riders (5.7%) reported having endured tooth accidents in mountain biking (Muller et al., 2008). Juniors experienced the most tooth injuries (5/50, 10%) compared to amateurs or professionals.

Subclinical microtraumatism of the scrotal contents

Frauscher, Klauser, and Stenzl et al. (2001) conducted an ultrasonographic survey imaging the scrotal contents of 45 amateur mountain bikers, aged17–45 years. Ninety-four percent of bikers presented with abnormalities of the scrotal contents compared with 16% of controls ($p < 0.001$). However, only 46% of the bikers presented with clinical symptoms.

Mitterberger et al. (2008) conducted a sonographic and clinical examination of 85 male mountain bikers (ages 17–45) and 40 on-road cyclists (range 15–46 years). Results showed that 80/85 (94%) mountain bikers and 24/50 (48%) on-road cyclists presented with abnormal findings on scrotal ultrasound (US) ($p = < 0.001$). Abnormal US findings in mountain bikers included scrotoliths (81%), spermatoceles (46%) and epidiymal calcifications (40%).

Table 3. Percent comparison of injury types.

Injury Type/Study	Romanow et al., 2014	Ashwell et al., 2012	Nelson and McKenzie 2011	Jeys et al., 2001	Becker et al., 2013	Aitken et al., 2011	Kronisch et al., 2002	Chow & Kronisch, 2002	Kronisch et al., 1996b	Kronisch & Rubin, 1994
Abrasion					316 (64%)	115 (39.8%)a	78 (38.6%)		22 (50%)	2 (3.3%)
Contusion					279 (57%)		39 (19.3%)		5 (11.4%)	7 (11.7%)
Torsion					72 (15%)					
Laceration			20.5%		62 (13%)		12 (5.9%)	16 (17.7%)	5 (11.4%)	10 (16.7%)
Strain					45 (9%)		7 (3.5%)	8 (8.9%)		3 (5%)
Fracture	173 (37.2%)	445 (25.3%)	26%	45%	32 (7%)	68 (23.5%)	39 (19.3%)	30 (33.3%)	5 (11.4%)	14 (23.3%)
Concussion/Intracranial injury and minor head injury	57 (12.3%)	101 11.2%)			23 (5%)	24 (8.3%)	11 (5.4%)	13 (14.4%)	4 (9.1%)	3 (5%)
Sprain					27 (6%)		14 (6.9%)		1 (2.3%)	9 (15%)
Joint dislocation					15 (3%)	14 (4.8%)			1 (2.3%)	3 (5%)
Joint inflammation					7 (1%)					
Internal organ injury	10 (2.1%)									
Other					23 (5%)		2 (1.0%)		1 (2.3%)	9 (15%)
Total # Injuries	465	1759					202	190	44	60

• Including data on lacerations.

Injury severity

The severity of an injury is an important factor to consider in determining the relative safety and risk level of any activity.

Hospital admission and operative treatment

Several studies indicate from 4.8 to 16% of injured mountain bikers required hospitalization (Aitken et al., 2011; Nelson et al., 2011; Romanow et al., 2014). Ashwell et al. (2012) reported that 8.5% of patients seen at a mountain clinic for injuries sustained while riding in the bike park were discharged to a higher level of care. Two of these were transferred by helicopter to a children's trauma center (a 12-year-old with suspected intrabdominal bleeding and a 10-year-old with a thoracic spine injury).

Jeys et al. (2001) reported that 19 patients (23%) needed operative treatment, some requiring multiple procedures with a prolonged hospital stay. Kim et al. (2006) reported that 38% of injuries and 66% of patients required operative intervention in their study of mountain biking injuries requiring trauma system admission. Dodwell et al. (2010) noted that 67 of 107 patients seen at a provincial spine referral center required surgical treatment and 31 patients (32.5%) required inpatient rehabilitation.

Injury severity score

Dodwell et al. (2010) reported injury severity scores (ISS) were available in 82% of patients with spine injuries incurred during mountain biking. The mean ISS was 15.7 (95% CI: 14, 17.4) and sixty-seven patients (62.6%) required surgical treatment. Kim et al. (2006) reported a mean AIS for head/neck, abdomen/pelvis, and chest was 3 (serious injury). The annual number of patients with severe (AIS ≥ 3 truncal, head, and spine) mountain biking injuries increased over the study period 1992–2002. In their study of competitive off-road bicycle racers Kronisch et al. (1996b) reported 16 riders with 44 injuries. Injury severity scores ranged from 1–5 (minor/moderate), with a mean of 3.0 (minor).

Clinical outcome

Catastrophic injury

The worst-case scenario in adventure and extreme sports is catastrophic injury. Catastrophic sports injuries are categorized by the National Center for Catastrophic Sports Injury Research (NCCSIR) as fatalities, nonfatal injuries (permanent severe functional disability) and serious injuries (no permanent disability but significant initial injury such as vertebral fracture without paralysis) (Kucera, Yau, Thomas, Wolff, & Cantu, 2015).

Catastrophic injuries may cause permanent neurological deficits (Ashwell et al., 2012; Dodwell et al., 2010; Kim et al., 2006) or even death (Kim et al., 2006; Jeys et al., 2001), which can be devastating to mountain bikers and their families and may also result in major long-term medical costs. Ashwell et al. (2012) reported 21 cases of vertebral fractures affecting injured mountain bikers aged 7–66 years. Although most fractures were compression fractures of the thoracic or lumbar spine without cord involvement, one patient did have a cervical spine injury resulting in quadriplegia.

During 2000–2011, 15,233 head and neck injuries (HNI) sustained during mountain biking were treated at US emergency departments (Sharma, Rango, Connaughton, Lombardo, & Sabesan, 2015). Although mountain biking had the lowest number of HNI among 7 extreme sports followed, it was the second riskiest sport with respect to neck fractures, with an incidence rate of 12.8 per 1,000,000 person-years (Sharma et al., 2015). The data in this study included all ages; however, teens and young adults accounted for the highest percentage of extreme sport injuries.

Dodwell et al. (2010) reported on a series of patients injured while mountain biking and seen at a provincial spine center in British Columbia during 1995–2007. During this period, 107 patients (102 M and 5F) ranging from 14-70 years of age, suffered spine fracture and/or spinal cord injury. Seventeen of the subjects (15.9%) were aged 14–20 years. Forty-three patients (40.2%) suffered spinal cord injuries. Of the 64 patients without cord injury, 20.3% had nerve root injuries and 4.7% had "stingers," transient quadriplegia, or other transient neurological deficits. Sixteen patients (15%) had a documented brain injury, ranging from concussion to more severe brain injury.

Kim et al. (2006) reported 63 of 399 patients, ages 2 to 70 years, sustained spine injuries during mountain biking and in 27 of those 63 cases, there was presence of spinal cord injury. Four patients were rendered paraplegic and eight became quadriplegic as a result of the injuries. Eight patients sustained central cord syndrome and seven patients sustained nerve root injuries. Of all patients with spine injuries, one-third required further care at a rehabilitation facility and two-thirds were discharged home.

Economic cost

Injury-related cost of care can be a significant financial cost for injured mountain bikers and health care in general Dodwell et al., 2010; Mitterberger et al., 2008. Few studies have reported cost associated with treatment of mountain bike injuries. Ashwell et al. (2012) reported that Canadians living outside of British Columbia were charged a flat fee of C$238; however, for non-Canadians the median charge was C$969.68 with a minimum of C$301.05 and maximum of C$2669.60.

Bentley, Macky, and Edwards (2006) reported on injuries to New Zealanders participating in adventure tourism and adventure sports over 12 months. Participation in MTB was associated with the second highest percentage and rate of injuries (after horse riding) but cost the most per patient at 148.2 NZ$.

What are the risk factors?

Our review revealed few studies which tested injury risk factors for correlation or predictive value.

Intrinsic factors

Age

Nelson and McKenzie (2011) reported that patients aged 14–19 years (12.4%) sustained a greater proportion of head injuries than did patients 8–13 years and >20 years (6.1%)

combined (IPR, 2.0;95% CI, 1.6–2.5). (Nelson et al., 2011). Additionally, patients aged 14–19 years (8.4%) sustained a greater proportion of TBIs than did patients aged 8–13 years and ≥ than 20 years combined (4.3%) (IPR, 2.0; 95% CI, 1.6–2.5). In contrast, patients aged 8–13 years (34.3%) sustained a greater proportion of upper extremity injuries than patients aged ≥14 years (26%) (IPR, 1.3: 95% CI, 1.2 to 1.5).

In their comparison of on- and off-road bicycling injuries in Tasmania, Jacobson, Blizzard, and Dwyer (1998) reported that proportionately more of the injuries to children > 10 years of age occurred off-road (81.8%, 166/203) than did injuries to older cyclists (50.3%, 181/360) and more often ($p < 0.001$) involved an injury to the head. Notably, helmet use was lowest in this group (28.6%).

Gender

Several studies of competitive and recreational mountain bikers report a variable risk of injury for male and female mountain bikers. Aitken et al. (2011) reported a higher injury rate for male (1.64 per 1000 biker exposures) than female (1.08 per 1000 biker exposures) recreational mountain bikers; however, this difference was not statistically significant. Aitken et al. (2011) also reported a higher, non-significant incidence of head injury in women ($p = 0.33$). In contrast, Kronisch et al. (2002), reported an overall injury rate of 0.77% (22/2,869 starts) for women versus 0.40% (71/17,500 starts) for men ($p = 0.03$) competitive mountain bikers. Overall, women were 1.94 times more likely than men to sustain an injury ($p = 0.01$) and 4.17 times ($p = 0.001$) more likely to sustain a fracture (Kronisch et al., 2002). Kronisch et al. (1996b) reported that in cross-country competition there was a significantly higher rate of injury to women than to men, whether injury rates were calculated as a percentage of total starts ($P = 0.04$) or by total exposure time ($P = 0.01$).

Nelson & McKenzie (2011) reported that a greater proportion of girls and women (6.1%) than boys and men (4.5%) were hospitalized (IPR, 1.4;95% CI, 1.1 to 1.7) as a result of mountain bike-related injury, although it is not clear to what extent these results reflected injury in a competitive setting. Notably, Romanow et al. (2014) reported a greater proportion of females among hospitalized subjects compared with controls (16% vs. 10%), although the result was not statistically significant.

Further research is required to determine the relative dangers posed by mountain biking among males and females.

Extrinsic factors

Equipment

Helmet usage is typically high among youth mountain bikers, especially given that many ski areas and downhill terrain parks require the use of helmets (Kotlyar, 2016). For example, Aitken et al. (2011) reported that all but one of the injured recreational mountain bikers at the Glentress Mountain Biking Centre in Scotland was wearing a helmet at the time of injury. However, an unexpected finding in one study (Ashwell et al., 2012), was the number of closed head injuries despite the mandatory helmet requirement. Of riders seen at the clinic, 11.2% (n = 101) had suffered closed head injury. Although most of these were minor, there were 8 cases in which patients had marked decline in neurologic function.

Romanow et al. (2014) reported that UE protective equipment (e.g., elbow or shoulder pads) was used more by hospitalized injured subjects than injured subjects who had been treated and released (23% vs. 11%, $p = 0.03$). At least half of the hospitalized subjects in their study wore one piece of non-helmet protective equipment, whereas 38% of non-hospitalized subjects did so. It may be that those who wear safety equipment are more inclined to engage in risky behavior and, by extension, more likely to suffer severe injuries (Romanow et al., 2014).

Exposure

Chow, Bracker, and Patrick (1993) reported that the more seriously injured group (requiring medical attention) reported riding more total hours each week (7.8 versus 6.3, $p < 0.01$) and more off-road hours each week (5.7 versus 4.8, $p < 0.05$).

Speed

Riding downhill, which is associated with increased speed, resulted in more injuries and increased odds of severe injury compared with flat and uphill riding in several studies (Kronisch et al., 1996b; Kronisch et al., 2002; Kronisch & Rubin, 1994). Romanow et al. (2014), adjusting for age and gender, reported that those bicycling faster than they typically would in similar conditions have more severe injuries (OR = 2.5; 95% CI: 1.2, 5.3) and resulted in a 2.6-fold increase in the risk of hospitalization.

What are the inciting events?

Nelson and McKenzie (2011) reported that the majority of mountain bike-related injuries in their study were attributed to falls (69.9%) or being thrown from the bike (14.1%). Most MTB injuries occur when the rider is descending a grade, whether in a downhill race or on the downhill portion of a cross-country race course (Bush et al., 2013; Nelson & McKenzie, 2011; Kim et al., 2006; Kronisch et al., 2002; Chow & Kronisch, 2002; Kronisch et al., 1996b; Chow et al., 1993).

A fall forward over the handlebars was not only the most common direction of falling in several studies, but it also led to injuries that were more severe overall (Becker et al., 2013; Dodwell et al., 2012; Chow & Kronisch, 2002). Notably, Dodwell et al. (2010) reported that 78 mountain bikers (75.7%) treated at a spine referral center sustained their spinal injuries with an "over the bars" mechanism. Of those going over the handlebars, 71 (91.0%) sustained direct impact primarily to their heads, and occasionally to the neck and face.

In contrast, Nelson and McKenzie (2011) reported that 8–13-year-olds treated in US emergency departments had the greatest proportion of injuries associated with being hit by an object (e.g., cars) but this is because the data included mountain-bike accidents that occurred on roads. Patients aged 8 to 13 years had a greater proportion of injuries caused by contact with the bike (8.6%) and being hit by something (4.4%) as compared with patients aged ≥ 14 years (4.7 and 1.3%, respectively) (IPR, 1.9; 95% CI, 1.3 to 2.7; IPR, 3.4; 95% CI, 1.9 to 6.4, respectively).

Other inciting factors associated with MTB injuries reported in the literature include riding errors or failures of judgement (Gaulrapp et al., 2001); unfamiliar terrain (Chow et al., 1993; Gaulrapp et al., 2001), collision with a stationary object (Kronisch et al.,

1996a, 2002), loss of control (Kronisch et al., 1996a, 2002), mechanical failure (Kronisch et al., 1996a); and poor judgement (Kronisch et al., 2002).

Injury prevention

There is presently no research published testing the effectiveness of injury preventive measures in mountain biking, including the pediatric and adolescent groups. However, a systematic review of studies evaluating child-targeted bicycle helmet legislation indicated a positive effect of bicycle helmet laws for increasing helmet use and reducing head injuries in the target population compared to controls (either jurisdictions without helmet laws or non-target populations). (Macpherson & Spinks, 2008). This finding is encouraging and may serve to inform injury prevention in MTB.

Suggestions for injury prevention

Recommendations for injury prevention in mountain biking tend to be intuitive with conclusions drawn from descriptive data and targeting mountain bikers of all ages.

- MTBTPs that cater to recreational bicyclists could be designed in such a way that limits the speed riders can gain by reducing the distance of straightaways or choosing to build trails in areas that are not as steep (Romanow et al., 2014).
- Injury prevention methods should include the strict separation of hiking and downhill trails as well as frequent inspection of the downhill trails for the presence of accidental obstacles (Becker et al., 2013).
- Promote activities such as rating difficulty of trails, promoting skill acquisition at bike-parks before going on the trails and promoting a safe riding attitude and skill training camps (Kim et al., 2006).
- Ensure that the bicycle and all components, particularly the tires, are of good quality and undergo regular maintenance (Kronisch & Pfeiffer, 2002).
- Downhill cyclists are wise to wear helmets that incorporate facial protection (Kronisch & Pfeiffer, 2002).
- Rider education programs to educate the recreational rider regarding proper trail selection (Kronisch & Pfeiffer, 2002).
- Suspension systems and shock absorbers to reduce the potential risk of scrotal disorders (Mitterberger et al., 2008).
- The use of mouthguards to protect against orofacial injuries (Müller et al., 2008).

Further research

There is an urgent need for coherent epidemiological research to study the distribution and determinants of mountain biking injuries among children and adolescents for the purpose of identifying and implementing measures to prevent their development and spread. Listed below and arising from our review are research questions and suggested areas of research:

- Examine the protective effect of specific pieces of equipment, as well as different helmet types (Romanow et al., 2014).
- Evaluate the clinical outcome of new shock-absorbing saddles and full suspension bikes may help to reduce saddle vibration and thus, the amount of microtrauma (Frauscher et al., 2001).
- Examine the role of protective knee and elbow equipment in trail cyclists (Kotlyar, 2016).
- Determine which trail features are associated with injury (Ashwell et al., 2012).
- Evaluate the long-term outcomes of bike park injuries and costs of care after injury (Ashwell et al., 2012).
- Elucidate the role of helmets and helmet types on spine and spinal cord injury, as well as the impact of other protective gear (Dodwell et al., 2010).
- Investigate the possible influence of extrinsic factors such as bicycle equipment, course design, and protective gear on injury rates and patterns. (Romanow et al., 2014; Kronisch et al., 1996a1996a).
- Is there an increased risk of going over the handlebars with hardtail (no rear suspension) vs. full suspension bikes?
- How effective are dropper posts vs. traditional seat posts in preventing over the handlebar injuries on downhill sections?
- What are the injury rates for different sized bikes, including 26″ vs. 27.5″ vs. 29″ tires, within each discipline of MTB? Does age play a factor in injury rates on the different sizes of off-road bikes within each discipline?

Disclosure statement

No potential conflict of interest was reported by the authors.

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