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Injuries in Mountain Biking and Implications for Care

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SUMMARY

Introduction. Mountain biking is a popular recreational activity that has a significant potential for injury.
Methods. This review paper integrates research studies and expert opinion. It examines the various types of mountain biking, associated patterns of injury, trends in the sport, impact on medical services, and expanded roles for health professionals in promoting preventive care and counseling on safe riding practices.
Results. Multiple studies on the frequency of mountain biking injuries suggests that findings may not be reflective of actual injury rates due to under-reporting, as well as inconsistencies in how injuries and injury severity are defined. Given these limitations, it appears that injury rates in mountain biking are on the high end of outdoor sports and that riding downhill is where most serious injuries occur.
Injuries occur most frequently to the upper and lower extremities, with fractures trending towards the upper extremities. Traumatic head injuries and cervical spine injuries are among the most severe injuries, and mountain biking accounts for a significant portion of activity related TBI and spinal injuries. The emergence of e-bikes contributes is attracting older riders to the sport, with potential consequences for increased injury.
Conclusions. The health care community can help in reducing injuries through avenues such as counseling patients and community members about safe riding practices, discussing appropriate gear, working with mountain bike parks to design safer trails and consulting with bicycle manufacturers to design safer bikes.

KEY WORDS

Mountain bike, mountain biking, cycling, wilderness, injuries, prevention, adventure

INTRODUCTION

Mountain biking has grown in popularity following its introduction in the 1970's, attracting riders seeking exercise, adventure, and competitive sport opportunities. In 2017, 8.6 million Americans engaged in mountain biking as a recreational activity (1). Mountain biking, like other adventure sports, is inherently risky; injury rates can be as high as 40 injuries per 1000 hours of riding (2-4). Advances in technology are creating new possibilities for riders, and with that, an expansion into areas of more extreme terrain, altitude, and isolation from medical services. E-bikes, which make pedaling easier through electric assist motors, are extending access for older and less fit riders into trails that had previously been beyond their physical and technical abilities. This article will explore types of mountain biking, examine injuries common to particular disciplines, and present a discussion of future trends so that health care providers may be better prepared to treat biking injuries and counsel patients on safe riding practices.

METHODS

The authors conducted a systematic review to examine the existing scholarly literature on mountain biking injuries. A search of two databases-- PubMed and Engineering Village (Elsevier)--was carried out by a medical librarian, covering the span from database inception to October, 2019. This review served to frame the dimensions of the literature

and to gain insight into new directions for research on this topic. Search strategies and retrieval results are as follows: PUBMED: (((mountain) AND (bike OR bikes OR biking))) AND (injury OR injuries OR injury OR injured) 131 articles. ENGINEERING VILLAGE: "mountain biking" and (technology or technologies or safety) 29 articles. The 160 articles were reviewed by the authors for relevance to the topic, study type, and levels of evidence. Of particular interest were articles focusing on injury patterns, technological innovations, and risk reduction. Exclusion criteria included non-English articles, articles that did not specifically concentrate on mountain biking as a recreational or sport activity and articles that did not present data analysis. Ultimately, 55 articles were identified as meaningful to the topic. A thematic analysis of the 55 articles found clustering in four areas: description of injury rates by type and demographic (33); injury case reports (6); review articles (6); and discussions on technology and safety (10).

DEMOGRAPHICS

Mountain biking has a global following. In the UK in 2005, 344,000 people were estimated to participate regularly in mountain biking. Germany had 3.5 million mountain bikers of 7.2 million total cyclists, and Switzerland and Austria had a combined total estimated at 800,000 mountain bikers (2). Like other "adventure sports," mountain biking participants tend to be younger males, but recent reports suggest that the sport is broadening its appeal to more women and older riders (6,1).

BIKING DISCIPLINES

The sport of mountain biking has become both more diverse and more specialized since its inception. The original concept of mountain biking has evolved over time to encompass subspecialties such as cross country, downhill, free ride, enduro, dirt jumping and more (see **table II**). There is significant overlap between the disciplines, but there are distinctions that are important to medical providers working with mountain bikers. As athletes strive to push the envelope, new niche areas emerge. The latest variant on an already intense sport is Heli-biking, where mountain bikers are dropped off on top of remote mountains.

RESEARCH ON INJURY PATTERNS

Although multiple studies have reported on the frequency and patterns of mountain biking injuries, study limitations suggest that findings may not be reflective of actual injury rates due to challenges in collecting data on all injuries and, more importantly, obtaining accurate data on the number of mountain bikers or mountain bike "exposures" (hours riding (3, 6, 12, 13). Additionally, investigation has been hampered by bike park (ski resort) policies that block sharing of injury and exposure data as reflected in the sale of lift tickets. In a study of Whistler Bike Park, this policy of non-disclosure prevented the calculation of injury risks or rates (10). These challenges are reflected in the widely differing estimates of injury rates, which range from approximately 1.5 to 43 injuries per 1000 hours at downhill mountain bike parks and approximately 2 -17 injuries per 1000 hours of cross country riding (2,3,4). The lower end of the estimates are comparable to the injury rate in downhill skiing and snowboarding of approximately 2 – 6 injuries per 1000 activity days (13). Serious injuries, defined as being limb or life threatening, occur at a rate of 2.5 per thousand hours of downhill riding, compared to 10 "catastrophic injuries" per million skier days at ski resorts, but direct comparison is impossible due to inadequate application of injury severity definitions (2,3,19).

Since mountain bike parks are reluctant to share their injury and ticket sales date, investigators have used surveys to calculate injury rates. In a prospective study of German downhill mountain bike riders, investigators found that in one season, 294 riders suffered 494 injuries, with 13% considered "serious" and a calculated injury rate of 16.8 per 1000 hours (14). A retrospective study of cross country riders found that 90% of riders reported at least one injury during the season, with 10% being "serious" and a calculated injury rate of only 1.1 per 1000 hours (15).

Abrasions and bruises are by far the most common injuries, mostly affecting the extremities, with conflicting data on the relative frequency of upper versus lower extremity injuries (16). Of injuries that result in fractures, the upper limb was injured at least three times as often as the lower limb. The clavicle was the most common site of fracture, followed by the distal radius and scaphoid (17,10). Another common injury to the upper extremity is wrist neuropathy, an overuse injury related to the vibration of the handlebars (16).

Helmets are almost always worn by mountain bikers (88% of riders report consistent helmet use) and have been shown to be effective (28% and 39% reduction in facial and head injuries, respectively) (18,16). Multiple studies have shown that concussions and more severe head injuries are common in mountain biking, ranging from 5% to almost 15% of all injuries (19,14). Of the cyclists with facial injuries, over half had facial bone fractures and 5 – 10% suffered tooth damage or loss. Among those who had tooth damage, only half of them were aware that avulsed teeth can be replanted (20). Young mountain bikers appear to be at the highest risk for head injuries, though it is not known if this is due

Table I. Literature review summary.

TITLE AUTHOR YEAR	STUDY DESIGN	STUDY FINDINGS
Investigative Studies on Injury Patterns and Rates		
Acute Injuries in Male Elite and Amateur Mountain Bikers: Results of a Survey. Stoop R. 2019	Cross-sectional observational study factors predicting injuries among elite and amateur riders.	No predictive factors for a severe injury event were found. Elite riders are at higher risk for an injury event due to their exposure time, but do not suffer more or more severe injuries than amateurs.
Complex shoulder girdle injuries following mountain bike accidents and a review of the literature. Lea MA. 2016	Cohort study of 104 patients with fractures following mountain bike injuries.	Fractures of the upper limb were the most common (88.5%) with the clavicle being the most commonly fractured bone (28.8%).
Cycling Injuries in Southwest Colorado: A Comparison of Road vs Trail Riding Injury Patterns. Kotlyar S. 2016	Retrospective chart review of injured road and trail cyclists.	The most common injuries were lacerations and abrasions (64%), upper extremity fractures (26%), head injuries (9%), and thoracic trauma (6%). Head injury was more common in road- vs trail-related trauma (16% vs 6%; P = .005), whereas thoracic injury was more common in trail riders (7% vs 2%; P = .053).
Vertigo in downhill mountain biking and road cycling. Lion A. 2016	Cross-sectional study of 102 downhill mountain bikers and 79 road cyclists to evaluate the prevalence of vertigo in daily living activities and following competitions or training sessions.	Downhill riders older than 30 reported vertigo more often than age-matched road cyclists. Vertigo causal factors were crash with head trauma in downhill riders and fatigue in road cyclists.
Acute hand and wrist injuries sustained during recreational mountain biking: a prospective study. Bush K. 2013	Prospective survey of hand and wrist injuries sustained in recreational mountain biking presenting to an emergency department over a 12-month consecutive period.	Analysis of 1,079 distinct injuries showed that 511 were sustained to the upper limb. Injury to the metacarpal and metacarpal phalangeal joints was the most common hand injury (52) followed by proximal phalanx and proximal interphalangeal joint (20).
Severe street and mountain bicycling injuries in adults: a comparison of the incidence, risk factors and injury patterns over 14 years. Roberts DJ. 2013	Retrospective cohort study using the Southern Alberta Trauma Database of all adults who were severely injured while street or mountain bicycling over 14 year period to compare incidence, risk factors and injury patterns.	Injury patterns were similar for both cohorts with trauma to the head (67.4%), extremities (38.4%), chest (34.1%), face (26.0%) and abdomen (10.1%) most common. Spinal injuries, however, were more frequent among mountain cyclists.
A prospective study of downhill mountain biking injuries. Becker J. 2013	Monthly e-mail-based prospective survey of 249 riders on patterns and causes of injuries to inform starting points for injury prevention measures.	Data confirms that downhill mountain biking is an extreme sport with a high risk of serious injury. Of 494 injuries, 65% were mild, 22% moderate and 13% severe, of which 41% led to a total restriction greater than 28 days. Strategies of injury prevention should focus on improvements in riders' technique, checking of local trail conditions and protective equipment.
Mountain bike terrain park-related injuries: an emerging cause of morbidity. Romanow NT. 2014	Case-control study describes the profile of bicyclists injured in bike terrain parks and examines risk factors for injury.	A higher proportion of hospitalized versus non-hospitalized cases suffered a head injury (22%), fracture (41%) or internal organ injury (32%). Upper extremity protective equipment (e.g. elbow or shoulder pads) was used more by cases than controls (23% vs. 11%, p = 0.03). The risk of severe injury may be reduced by encouraging bicyclists to control speed or by modifying trail design to limit the opportunity to gain speed.
Injury and illness in mountain bicycle stage racing: experience from the Trans-Sylvania Mountain Bike Epic Race. McGrath TM. 2012	Analysis of injury and illness patterns associated with mountain bike stage racing.	In 52 competing athletes there were 30 separate medical encounters, with a total of 34 injuries/illnesses. 65% were classified as injury, and 35% were classified as illness. Skin and soft tissue injuries/illnesses were the most prevalent.

TITLE AUTHOR YEAR	STUDY DESIGN	STUDY FINDINGS
The epidemiology of mountain bike park injuries at the Whistler Bike Park, British Columbia (BC), Canada. Ashwell Z. 2012	A 6 month retrospective chart review of injured bike park cyclists presenting to the Whistler Health Clinic.	Specific injury diagnoses include 420 fractures in 382 patients. Upper extremity fractures predominated (75.4%), 11.2% had a traumatic brain injury. 8.5% were transferred to a higher level of care: Findings highlight the need for continued research into appropriate safety equipment and risk avoidance measures.
The epidemiology of sports-related injuries in older adults: a central European epidemiologic study. Kammerlander C. 2012	Retrospective chart review of adults aged 65 years and older who were treated for sports-related injuries.	The yearly number of injuries doubled during the study period (1996-2007). Nearly 75% of all injuries occurred during alpine skiing, cycling or mountain climbing. The median Injury Severity Score was 4. Minor injuries and wounds (40%) were recorded most commonly followed by fractures (27%), sprains, ligament injuries (19%) and injuries of muscles and tendons (6%).
Injuries in mountain bike racing: frequency of injuries in endurance versus cross country mountain bike races. Lareau SA. 2011	A cross-sectional study of riders at mountain bike endurance races to determine experience level, previous injuries, rider demographics, and treatment received.	7.2% of cross-country riders and 4.7% of endurance racers were injured during the race. There was no increased risk of being injured in a race over an endurance race (odds ratio 1.6, 95% CI [0.50, 2.92]). Lacerations and abrasions were the most common injuries in both events.
Gonadal function in male mountain bikers. Yamaner F. 2011	Pre and post race assessment of biochemical markers of gonadal function.	Basal hormonal levels including insulin, leptin, LH, FSH, SHBG, TT, glucose, and homeostasis model assessment scores were similar between the groups. However, bioT and cFT levels were significantly lower ($p \leq 0.05$) in the mountain bikers than those in the controls. This alteration cannot solely be explained by testicular dysfunction.
Mountain biking-related injuries treated in emergency departments in the United States, 1994-2007. Nelson NG. 2011	A retrospective analysis of injuries with data from the National Electronic Injury Surveillance System of the US Consumer Product Safety Commission for patients aged >8 years from 1994 through 2007.	Nationwide, an estimated 217,433 patients were treated for mountain bike–related injuries in US emergency departments from 1994 to 2007, an average of 15,531 injuries per year. The annual number of injuries decreased 56%, from a high of 23,177 in 1995 to 10,267 in 2007 (P\.001). The most common injuries were upper extremity fractures (10.6%) and shoulder fractures (8.3%). Patients aged 14 to 19 years sustained a greater proportion of traumatic brain injuries (8.4%) than did patients aged 8 to 13 years and20 years combined (4.3%). A greater proportion of female riders (6.1%) than male riders (4.5%) were hospitalized.
The perception of causes of accidents in mountain sports: a study based on the experiences of victims. Chamarro A. 2009	Online convenience survey of 135 adults who were injured in "mountain sports" (mountaineering 44, climbing 41, skiing 26, hiking 16, XC MTB 7, mountain racing 1)	No breakout of data from mountain bikers. Factors leading to injuries were: behavioral events (judgment and decisions) (41%), environmental events (weather, terrain)(39%), medical events (fatigue) (12%) and equipment (7%).
Dental injuries in mountain biking--a survey in Switzerland, Austria, Germany and Italy. Müller KE. 2008	Convenience survey of 423 male European mountain bikers about dental injuries and knowledge.	27 (5.7%) had a dental injury. 52% of total knew an avulsed tooth could be replaced, 72% were aware of mouthguards but only 4.4% used them.
Do mountain bikers have a higher risk of scrotal disorders than on-road cyclists? Mitterberger M. 2008	Cross sectional analysis of scrotal US of 85 mountain bikers (age 27 – 45) and 50 road cyclists (age 15 – 46).	94% of mountain bikers and 48% of road cyclists had scrotal abnormalities on US. Testicular and extra-testicular calcifications were the most common findings in mountain bikers. Clinical significance is unclear.

TITLE AUTHOR YEAR	STUDY DESIGN	STUDY FINDINGS
Impaired anal sphincter function in professional cyclists. Sauper T. 2007	Cohort study of rectal exam and manometry on 19 professional mountain bikers (at least 6000km training in the past year) with 18 non (or minimal) cyclists.	Cyclists had higher sphincter volumes, resting and squeeze pressures.
Adventure tourism and adventure sports injury: the New Zealand experience. Bentley TA. 2007	Retrospective data analysis of approximately 15,000 injury claims related to "adventure sports" in NZ.	Mountain biking resulted in 12.4% of the claims (after horse riding (17%), "tramping" (13.4%) and tied with surfing). The injury rate per 1000 participants was 11, second to horse riding at 20.
Extreme mountain bike challenges may induce sub-clinical myocardial damage. Ortega FB. 2006	Before and after (pre and post race) assessment of blood levels of Troponin I, myoglobin, creatine kinase, urea and creatinine analysed. eight riders in a demanding mountain bike race (vertical climb 2430 meters)	All blood markers increased during the race with all subjects having post-race myoglobin above the upper normal limit. Troponin I increased significantly but no subjects had a level considered indicative of myocardial infarction.
Mountain biking injuries requiring trauma center admission: a 10-year regional trauma system experience. Kim PT. 2006	Retrospective review of trauma registries and charts from three trauma centers in BC that service very popular mountain biking areas and downhill parks (Whistler) from 1992 - 2002.	399 patients with 1092 injuries. Number of injuries increased over the time period. Young males were most commonly injured with orthopedic injuries in 46%, head and spine (12% each), chest and facial (10% each), abdominal (5%) and GU (2%). 66% of patients required surgery and one patient died. The authors state an injury prevention (primarily outreach) program was successfully implemented.
Gender differences in acute mountain bike racing injuries. Kronisch RL.2002	Study of injuries that impacted completion of a Mammoth Mountain off-road cycling race by surveying patients at the first aid station or local hospital during the race.	Injury rate was 0.77% for women and 0.4% for men during the 7 year study. Fractures represented the injury to 45.5% of injured female participants and 21.2% of injured male participants. Women were 1.94 times more likely than men to sustain an injury and 4.17 times more likely to sustain a fracture.
Mechanisms of injury in competitive off-road bicycling. Chow TK. 2002	Surveys of injured cyclists during 7 off-road events	Of 97 injured riders, 74% were male and 26% female. Injuries from falling forward were more common than falling to the side. Falls forward were more likely to cause significant injury compared to falling to the side. 70.5% of injuries invoked the extremities.
Abdominal injuries caused by bicycle handlebars. Erez I. 2001	Retrospective study of children admitted with injuries from bike handlebars	Out of 76 patients, 12 had handlebar imprints on the hypochondrium, and 25 had an isolated rupture of the spleen or liver. Of that 25, 5 patients required surgical intervention.
Mountain biking injuries in rural England. Jeys LM. 2001	Prospective study of patients during 1 year presenting with mountain biking injury.	84 patients were identified. Most accidents occurred in the summer, most commonly in August. 23% of patients required operative management. The most common injuries were clavicle fractures (13%), shoulder injuries (12%), and distal radial fractures (11%)
Central liver hematomas caused by mountain-bike crashes. Nehoda H. 2001	Retrospective chart review of 52 bike associated accidents in 1995-1998 that were admitted to a trauma ward in University Hospital of Innsbruck, Austria	52 patients were admitted. 8 presented with a subcapsular liver hematoma. None required operative management. The injuries were associated with a form of bar-ends used on mountain bikes which has sense been removed from the market. Only one patient presented with a liver hematoma secondary to mountain biking in 1998 and no patients had that presentation in 1999-2000 in that hospital.
US findings in the scrotum of extreme mountain bikers. Frauscher F.2001	Cohort study of scrotal ultrasound results in male subjects with extensive off-road biking activity compared to non-cyclists -Follow up study with larger sample size of article 56	94% of the mountain biker group had abnormal scrotal findings on ultrasound and 46% had intermittent scrotal tenderness/discomfort but no trauma. 16% of the control group displayed abnormal US results.

TITLE AUTHOR YEAR	STUDY DESIGN	STUDY FINDINGS
Injuries in mountain biking. Gaulrapp H. 2001	Large cross-sectional survey answered by 3873 athletes	Mountain bikers responding to the survey reported an overall injury risk rate of 0.6% or 1 injury per 1000 hours of riding. Risk factors included poor road conditions, poor judgment of the situation, or excessive speed. 14% of reported injuries were the result of hitting some part of the bike. 75% of injuries were minor (contusions or simple skin wounds) however 10% required hospitalization.
Subclinical microtraumatisation of the scrotal contents in extreme mountain biking. Frauscher F. 2000	Cohort study of scrotal ultrasound results in male subjects with extensive off-road biking activity (45 participants) compared to non-cyclists (31 participants)	96% of biking group had pathological abnormalities identified on scrotal ultrasound. 16% of control group displayed abnormal US results. 49% of biking group had scrotal tenderness, discomfort, or suspicious findings on exam. None of the control group reported an abnormal exam.
Forearm and wrist fractures in mountain bike riders. Rajapakse B. 1996	Retrospective chart review and survey of patients who had a forearm fracture secondary to mountain biking at Wellington Hospital between July 1992-July 1994	Mountain biking was the cause of forearm fractures in 37 patients with 25 patients agreeing to participate in a survey. Most common site of fracture was in the distal third of the forearm and most common fracture was of the radial head. Average time off of work due to the injury was 28 days. Out of 25 patients, functional assessment marked 15 as excellent, 5 as satisfactory, 4 as unsatisfactory and 1 as poor.
Acute injuries in off-road bicycle racing. Kronisch RL. 1996	Descriptive study of injuries sustained during a competitive racing event at Mammoth Mountain in July of 1994.	Out of 3624 participants, 16 sustained injuries that prevented them from completing their even, (injury rate of 0.4%). 81.2% of injuries occurred while going downhill. Injury severity was increased when riders were thrown from the bike.
Recreational mountain biking injuries. Aitken SA. 2011	Retrospective review of mountain bike injuries presenting to five facilities in Scotland from July 2007 through June 2008.	The injury rate was 1.54 injuries per 1000 biker exposures. Men were more commonly injured than women, with those aged 30-39 years at highest risk. The most common types of injury were wounds, skeletal fracture and musculoskeletal soft tissue injury. Joint dislocations occurred more commonly in older mountain bikers. The limbs were more commonly injured than the axial skeleton. The highest hospital admission rates were observed with head, neck and torso injuries. The effect of protective equipment: Type of helmet (full face, XC, Skater) did not affect injury rates. 68% with shattered helmet had no head injury. LE body armor was associated with fewer wounds but a trend towards more fractures. No effect of UE armor. More injuries with flat pedal vs "quick release" pedals. Slightly higher injuries with full suspension than hard-tail bikes.
Acute injuries from mountain biking. Chow TK. 1993	Survey of members of 2 Californian off-road bicycling organizations	58.4% response rate to survey. 82.8% were male. 84% had been injured while riding off-road bikes with 51% reporting injury within the last 12 months. 26% of reported injuries required professional medical care and 4.4% required hospitalization. 12% sustained a fracture or dislocation. 88% report helmet use.
The magnitude of translational and rotational head accelerations experienced by riders during downhill mountain biking. Hurst HT. 2018	Observational study of varying effects of course design.	Injuries and course design influences the number and magnitude of accelerations. Downhill riders may be at risk of sustaining traumatic brain injuries. Course design has an important influence on the number and magnitude of accelerations.

TITLE AUTHOR YEAR	STUDY DESIGN	STUDY FINDINGS
Case Reports and Case Series		
Spinal column and spinal cord injuries in mountain bikers: a 13-year review. Dodwell ER. 2010	Case series report BC, Canada provincial spine referral center 1995 – 2007.	102 men and 5 women, mean age 32.7yrs. 74% had C-spine injuries. Forty-three patients (40.2%) sustained a spinal cord injury. Of those with cord injuries, 18 (41.9%) were American Spinal Injury Association (ASIA) A, 5 (11.6%) were ASIA B, 10 (23.3%) ASIA C, and 10 (23.3%) ASIA D. Sixty-seven patients (62.6%) required surgical treatment. Of the 43 patients (40.2%) seen with spinal cord injuries, 14 (32.5%) improved by 1 ASIA category, and 1 (2.3%) improved by 2ASIA categories. Two patients remained ventilator-dependent at discharge.
Benign paroxysmal positional vertigo in mountain bikers. Vibert D. 2007	Case report of 4 mountain bikers with benign paroxysmal positional vertigo (BPPV) after mountain biking without trauma.	Symptoms resolved spontaneously in 2 and with physiotherapy in the other 2.
Acute cervical spine injuries in mountain biking: a report of 3 cases. Apsingi S.2006	Case reports of 3 cervical spine injuries from mountain biking.	All three had severe injury with permanent paralysis. All three were going downhill and fell over the handlebars.
Bicycling-induced ulnar tunnel syndrome. Kalainov DM. 2003	case report	41 year old male developed bilateral ulnar tunnel syndrome during a week of significant cycling. Symptoms improved with non-operative treatment measures
A dangerous design for a mountain bike. Alvarez-Segui M. 2001	Case study	Case study of man who's death was deemed a consequence of mountain biking secondary to a ruptured diaphragm
Mountain bike injuries and clipless pedals: a review of three cases. Patel ND. 2004	Case Series	Three cases of off road cyclists with isolated soft tissue injuries to the right lower leg, caused by the chain ring as they struggled to release their feet from clipless pedals. Correct adjustment of the pedals to facilitate quick release of the feet is required to prevent such injuries.
Review Articles		
Pediatric and adolescent injury in mountain biking. Caine DJ. 2018	Review of injuries affecting children and adolescent mountain bikers, risk factors involved, and injury prevention strategies.	Upper extremity injuries were most common except in adolescents where head injury and traumatic brain injuries are greater. Reducing mountain biking-related injuries will require multiple strategies that integrate approaches from education, engineering, and evidence-based safety measures and their enforcement.
Mountain Biking Injuries. Ansari M. 2017	Literature review	Injury patterns are changing over time. Recommends active injury monitoring systems and standardized injury definition and implementation of an injury surveillance program.
Mountain biking injuries in children and adolescents. Aleman KB. 2010	Review article to synthesize information of injury patterns.	Examines causation and risk factors associated with injury among young mountain bikers and makes recommendations to minimize trauma and enhance optimal performance.
Mountain biking injuries: a review. Carmont MR. 2008	Review article of 2 other review articles, 17 case controlled studies, 4 case series and 5 case reports.	Summarizes injury rates and patterns. Injury rates of 0.37 and 4.34 per 100 hours for XC and DH respectively. Males 20 – 39 most often injured, but females trend towards more serious injuries. 13% of sports related head trauma are due to all types of cycling. Helmets reduced head injury 39%. UE limb "commonly injured". Radial head fx most common fx (39%). Abdominal viscera injuries much reduced following campaign to remove "bar ends". Perineal and scrotal abnormalities on US care common, but clinical significance is unclear. LE injuries are common.

TITLE AUTHOR YEAR	STUDY DESIGN	STUDY FINDINGS
Mountain biking injuries: an update. Kronisch RL. 2002	Literature review of injuries in off-road bicyclists.	Women are outnumbered by men as participants of the sport but have higher rates of injury. Significant injuries happen more often during competition; however overuse injuries are common at both training and competitive levels. Risk of injury is reduced with appropriate conditioning and equipment, and appropriate trail selection.
Off-road cycling injuries. An overview. Pfeiffer RP. 1995	Review article	Injuries per race in competition range from 0.2-0.39% while recreational rider injury rate per ride is 0.3%. 20-88% of riders surveyed report sustaining an injury within the last year of participation. Most injuries involve the extremities. Off-road riders sustain higher rates of fractures, dislocations, and concussions than on-road riders.
Technology, Safety, and Risk Reduction		
The impact of an extreme sports event on a district general hospital. Carmont MR. 2005	Narrative description of the impact of an organized mountain bike event on a district hospital.	Annual ED visits were 35 per 24 hours. 52 riders reported 61 injuries with 24 riders being treated at the hospital (28% increase in attendance). One was admitted and one transferred. The authors state "extreme sports events can have considerable impact on small district general hospitals."
Wilderness medicine: strategies for provision of medical support for adventure racing. Townes DA. 2005	Single author narrative discussion.	Reviews what adventure racing can be and discusses the challenges to providing medical support in what are often severe and remote locations.
The influence of repeated chin bar impacts on the protective properties of full-face mountain biking helmets Warnica, Meagan J. 2016	Engineering equipment analysis of multiple impacts and helmet types influencing protective properties of full-face helmets.	Peak accelerations for all trials were below the 300 g pass/fail criterion used in some testing standards. Multiple impacts reduced helmet protective properties, most noticeably at the higher impact velocities. Helmet protective properties were associated with local chin bar characteristics at higher impact velocities.
Transference of 3D accelerations during cross country mountain biking. Macdermid PW. 2014	Describes relationship between vibration mechanics and their interaction with terrain, bicycle and rider comparing 26- and 29- wheels.	Overall accelerometer data showed location differences between the point of interface of bike-body compared to those experienced at the lower back and head. The reduction in accelerations at both the lower back and head are imperative for injury prevention and demonstrates an additional non-propulsive, muscular, challenge to riding.
Mountain biking injuries: fitting treatment to the causes. Kronisch RL. 1998	Narrative article	Discusses how overuse injuries can be caused by improper fit of bike equipment and recommended modifications
Bicycle helmet effectiveness is not overstated. Olivier J. 2017	Review article to estimate helmet effectiveness from cases and available exposure data.	Despite potential weaknesses with case-control study designs, the best available evidence suggests that helmet use is an effective measure of reducing cycling head injury.
Bicycle safety and bicycle standards Mitchell, David A. 2006	Review of US federal regulations on bike safety and recommendations for minimum mechanical requirements on more aggressive mechanical loading imparted by mountain biking.	F 2043 standard was developed to form the design basis for other strength and durability test standards. F 2273, Test methods, for Bicycle Forks provides the various mechanical tests that may be applied to bicycle forks in general. Worldwide cooperation in the development of consistent standards ensures enhanced safety and lower cost to manufacturers and consumers.

TITLE AUTHOR YEAR	STUDY DESIGN	STUDY FINDINGS
Environmental, safety and management issues of unauthorised trail technical features for mountain bicycling. Pickering, Catherine. 2010	Assessment of the social, environmental and management impact associated with the increase in unauthorized enhancement of technical trail technical features.	In bike areas with unauthorized features such as jumps and bridges, nearly two thirds had low to moderate safety. Options for land managers in dealing with unauthorized trail technical features all present social, financial and environmental limitations and are a challenge that often has no easy solution.
Wilderness event medicine: planning for mass gatherings in remote areas. Burdick TE. 2005	Review article, single author recommendations on planning for wilderness events (which includes mountain biking).	Discusses pre-event planning, medical treatment at the event and post-event tasks.

Table II. Disciplines of Mountain Biking

Discipline	Description	Relative Popularity	Relative Injury Rate	Equipment Features
Cross Country	Prefer single-track trails into scenic areas with a mixture of up and down hill riding.	Most popular	1.5 injuries per 1000 rider days (3). 24 per 100 riders during Olympic competition (4).	Light weight, less "travel" by shocks, often clipped into pedals. Other than a helmet, minimal protective gear.
Endurance and Adventure Racing	Extreme form of cross country where riders compete on time in remote areas on rides that may continue over days (5,6).	Niche, but growing	Minor injuries (mainly abrasions) very common (~60% of riders in a multi-stage race). Severe injuries very low (28).	Similar to cross country, riders often need to carry their own repair and first aid gear.
Downhill	Often use ski lifts to access downhill trails. The object is to go quickly down the mountain, preferably on single-track, with manmade features an option. Over 250 downhill MTB parks worldwide in 2018 (9).	Second most popular and growing fast.	High (up to 40/1000 hours) Severe injuries including concussions and cervical spine injuries accounted for 25% of trauma center admissions in British Columbia (10).	Heavier bikes, flat pedals, a lot of "travel", front fork at a lower angle. Full face helmet, full body protective gear encouraged.
Enduro	In between cross-country and downhill. Riders ride/race up hill to then ride/race downhill.	Third	Intermediate (9.4 injuries per 100 riders during races) (11)	Intermediate features (weight, travel and fork angle), usually flat pedals. Full face helmet (maybe detachable chin), full body protective gear encouraged.
Free Ride	Riding down mountains, often above treeline (or desert) where the rider can choose or make his/her own trail. "Red Bull Rampage," is the epitome of this style.	Niche	Very high (12)	Very large shock travel, minimal gearing. Full face helmet, full body protective gear mandatory.
Dirt Jumping	Using man-made or (rarely) natural features to do big jumps and tricks while in the air.	Niche	No data	Smaller mountain bikes with no or only front suspension, often single-speed. Full face helmet, full body protective gear mandatory.

to the mechanism of injuries or anatomic and physiologic differences (21).

A 10-year retrospective analysis of the British Columbia Trauma Registry found that of 399 injured mountain bikers admitted to trauma centers, 12% had head injuries and another 12% had spinal injuries (22). Traumatic spinal injuries, with subsequent paralysis, are among the most catastrophic injuries in sports. Two studies in British Columbia found that one quarter of trauma center admissions involving spinal injuries were due to mountain biking and that 42% of these injuries led to complete paralysis (25,26).

The literature on concussions naturally focuses on falls as the major cause of injury, but a recent study of translational and rotation head accelerations during downhill riding, using triaxial accelerometers, demonstrated forces sufficient for causing traumatic brain injuries from riding the course without falling. This in turn, raises the risk of subacute brain injury, especially in youths (23).

Women tend to suffer fractures and back injuries more frequently than males, possibly because they are lighter and typically less experienced-leading women to go over the handlebars more frequently than their male counterparts (28,7,21,29). Men and women also attribute their injuries to different factors. According to a German study, the majority of women involved with mountain biking accidents attributed their mishaps to overexertion or not knowing their limitations. Men in the study tended to attribute their injuries on risk taking behaviors and excessive speed (17).

IMPACT OF NEW TECHNOLOGIES

As both a recreational activity and an industry, mountain biking is incorporating advances in technology that are broadening the demographics of the sport, as well as encouraging riding activity in increasingly diverse and challenging terrain. These developments have implications for rider safety, risk reduction, and health care.

E-BIKES

By amplifying the pedaling power of the rider, E-bikes make the challenge of biking less exhausting, especially at high altitudes and on difficult terrain. This is particularly true for older, less fit, or less experienced riders (26). Analysis of global recreational and adventure biking activities shows a growing consumer preference towards E-bikes, especially among the "Boomer" generation, who sees them as a means to new riding experiences (27). They are the fastest-growing bicycle market segment, with sales of electric bikes growing more than eightfold since 2014 (28). Access to remote areas via E-bike can expect to accelerate given changes that relax restrictions on wilderness areas, including U.S. national parks. Recently, Order No. 3376 was signed by the Department of the Interior, which classifies all E-bikes as non-motorized vehicles on federal lands that are managed by the department and allows them to go anywhere a human-powered bicycle can go (29).

WHEEL MODIFICATIONS

Trends in mountain bike riding are closely linked to improvements and innovations in bike technology. The impact that technological advances will have on injuries, however, is still not clear. One major trend over the past decade has been an evolution in wheel size, which now spans 26", 27.5" and 29" diameters. While debate continues about the ideal wheel and tire size, at least one study has quantified what riders perceive: that the larger wheels allow one to roll over objects more easily (30). Whether or not this has led to decreased injuries is a matter of debate. Many

Table III. Injuries

Upper extremity	**27 – 74% (24)**	**Metacarpal and MCP injuries most common (25).**
Lower Extremity	6 – 39% (24)	Typically from a sideways fall (21)
Head/Neck/Face (HNF)	6 – 29% (24)	Typically from falling over the handlebars. HNF injuries more common in women, children and adolescents (21) 6% reported dental injuries (20)
Causes of injury (14)	Riding errors	72%
(multiple causes possible)	Trail conditions/Obstacles	47%
	Fatigue	10%
	Weather	8%
	Collision with rider	2%

riders report larger wheels merely allow them to go faster and over smaller obstacles until they hit a larger obstacle they would not have attempted with smaller wheels, leading to a sudden stop and crash. As for race performance, two studies have demonstrated faster XC race times with the 29" wheels, and one study showed no difference between 26", 27.5" and 29" wheels, with most riders preferring the larger sized wheels (30).

FRAME INNOVATIONS

Frame manufacturers are developing full suspension bikes with multiple pivot points and pivots in novel placements to allow the rear wheel to move backwards and roll over obstacles more easily (31). Again, we do not know how this will impact injuries. Another widely adopted innovation for mountain bikes is the "dropper seat post". This allows riders to raise and lower their seat post and saddle as they ride. While it was designed for comfort and performance, some believe it has helped decrease over-the-handlebar falls by allowing riders to quickly lower the saddle for downhill stretches (32).

PROTECTIVE GEAR

Helmets are probably the most important, and nearly universally adopted, piece of safety gear for mountain biking. Helmets, especially for downhill, all mountain and dirt jumping mountain biking should have a face shield and be ASTM F1952 certified, if purchased in the US (there are other certifications for European manufacturers). Multiple studies have demonstrated that bicycle helmets protect riders from serious brain injury, with reductions in severe TBI ranging from 65% to 88% (33). A recent innovation is the detachable chin guard, which allows the rider to remove it on the climb for comfort, and then attach it for safety for the downhill.

Even with near universal use of helmets, the rate of serious TBI at roughly 5 – 15% of injuries is still too high (20,15). Consequently, helmet manufacturers are experimenting with new designs and materials to reduce impacts on the brain. One popular design is the "Multi-directional Impact Protection" or MIPS helmet. These helmets are designed to allow the helmet to move and rotate without transmitting this force to the scalp. Unfortunately, testing has not found significant added protection from these designs (34).

DISCUSSION

As outlined, mountain biking poses a high potential for injury, both from accidents, as well as from exposure to extreme conditions. As documented by Kim, et al, the health care community may help reduce injuries through avenues like counseling patients and community members about safe riding practices and appropriate gear, working with mountain bike parks to design safer trails, and working with bicycle manufacturers to design safer bikes (23).

An effective first step for clinicians could be a discussion of safe mountain biking practices at a local cycling club meeting. An obvious focus would be the use and selection of protective gear. Clinicians should have a thorough understanding of the different types of riding disciplines in order to counsel appropriately. For example, a dedicated cross-country rider might balk at wearing a full-face helmet and a full set of body armor since the extra weight and heat retention from such gear is highly impractical. A downhill rider, however, would likely be more receptive since the benefit of extra protection overrides other concerns. One key goal for clinicians is to simply underscore the critical importance of a reasonably new helmet that fits well. Clinicians can also advise bikers on the importance of having a bike properly fitted, which has been shown to reduce overuse injuries, and may also reduce crashes and subsequent acute injuries (33).

Discussions on the health risks of mountain bike riding should also include chronic medical conditions faced by older active patients. The use of E-bikes, increasingly popular among this demographic, can have disastrous unintended consequences, especially when coupled with underlying medical conditions. Riders may find themselves on trails that overtax their technical skills or lack the necessary reflexes to cope with the increased speeds of electric assist pedaling. Novice E-bikes riders may simply be unprepared to manage an unexpected event like a depleted battery, finding themselves stranded and far from assistance.

Health care providers can have an important role in improving the design and safety of biking equipment. That can include taking a consulting role to contribute expertise on anatomy, physiology, and trauma, or engaging in research to analyze the impact of technology and design modifications on injury patterns. The publication of case reports on mountain bikers with subcapsular hematoma of the liver associated with handlebar bar-ends quickly led to the removal of bar-ends on bikes, and this injury virtually disappeared among mountain bikers (35).

As noted, mountain bike parks have historically shielded their data on park usage and injuries from public scrutiny. By working with legislators and park managers, the health care community can spotlight this issue to advocate for greater transparency of injury data. In countries where mountain bike parks operate at least partially on public lands, a case could be made that the public has a right to this data, and

that the public health benefit of obtaining this information outweighs proprietary business claims.

Health care providers also need to be concerned about the unusual demands that extreme sport events can place on local medical services and develop strategies accordingly. In the Fort William Mountain Bike Race in Scotland, for example, the one bed emergency department of the nearest hospital is staffed by three nurses and two junior physicians, with a surgeon, physician, and an anesthetist on call. They are over two hours away from care centers with neurosurgery, cardiothoracic surgery, or orthopedic surgery capabilities. The race weekend saw local emergency department visits increase by 28%, calling attention to the need for advance planning with respect to staffing and supplies (36).

SUMMARY

Mountain biking is an exciting, demanding, and growing worldwide sport that, while offering great cardiorespiratory health benefits, has a higher rate of injury than most other common recreational activities. Advances in bike technology, such as pedal assist E-bikes, are opening up trails to a broader spectrum of riders who may be older, less fit, less experienced, and consequently more vulnerable to injury. Extrinsic factors can make accurate calculation of injury rates problematic. Most injuries are minor abrasions and contusions, but despite improvements in bike construction, headgear and body armor, there is still potential for catastrophic injuries to the head and spine, with children and adolescents at an increased risk. Healthcare providers should be aware of the injuries suffered by mountain bikers in an effort to improve their care, and to reduce injuries through education, research, public awareness and even promoting legislation, when needed.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (37).

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