EVALUATION OF INTRINSIC AND EXTRINSIC FACTORS ASSOCIATED WITH INJURY RATES AND PATTERNS AMONG RECREATIONAL SKIERS AND SNOWBOARDERS AT A COLORADO SKI RESORT

by

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A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

Epidemiology Program

2018

This thesis for the Doctor of Philosophy degree by

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Evaluation of Intrinsic and Extrinsic Factors Associated with Injury Rates and Patterns among Recreational Skiers and Snowboarders at a Colorado Ski Resort

Thesis directed by Professor R. Dawn Comstock

ABSTRACT

Over 10 million people participate in skiing and snowboarding in the United States (U.S.), including 500,000 Colorado residents. Accordingly, an estimated 600,000 patients with skiing- or snowboarding-related injuries are treated in physicians' offices, emergency departments, and hospitals annually. These injuries are often severe, as measured by severity scores and long-term sequalae, and have significant associated personal and societal financial costs. While prior studies have shown the most effective approaches for injury prevention are multifactorial, little research has been conducted on how environmental factors contribute and interplay with individual characteristics to influence skiing- and snowboarding-related injury patterns in the U.S. A classic etiological model of sport-related injury states that injuries result from complex contributions of intrinsic factors (e.g., demographics, skill level) and extrinsic factors (e.g., weather, crowdedness), instigated by inciting events (e.g., fall, collision). The purpose of this study was to identify influential independent factors related to injury rates and patterns among recreational skiers and snowboarders at Winter Park Resort, one of the largest resorts in the U.S. This study used data collected from the East Grand Community Clinic and Emergency Center (a combination primary care and trauma facility located at the base of the resort), Winter Park Resort Ski Patrol, and weather records provided by resort management. The goals of this research were to contribute to the evidence base that informs decision-making surrounding safety at resorts, and to ultimately reduce the frequency and severity of skiing- and snowboarding-related injuries.

The form and content of this abstract are approved. I recommend its publication.

Approved: R. Dawn Comstock

This dissertation is dedicated to my parents, Kim Pierpoint and Paul Liscom, my brother, David Pierpoint, and to my partner, Justin Hellwinkel.

ACKNOWLEDGEMENTS

This dissertation would not have been possible without the support and encouragement from many people. First, I am sincerely grateful for my committee members who provided strong mentorship throughout my doctoral training. I would like to thank my advisor, Dr. Dawn Comstock for continuously pushing me to improve my skills as an epidemiologist while simultaneously allowing me to grow as an independent researcher. Dr. Comstock provided an astounding amount of opportunity for professional development and gave me the freedom to pursue my own research interests in my own way. Dr. Tessa Crume was an unwavering advocate of mine and worked tirelessly with me to improve my writing skills. Dr. Gary Grunwald was a vital member of my committee who encouraged critical thinking and meaningful application of statistics. Dr. Zachary Kerr has set a tremendous example of what it means to pursue research with integrity and tenacity. Without Dr. Morteza Khodaee's vision for injury prevention at Winter Park and dedication to his clinical practice, this work simply would not have been possible. Thank you all.

Research is not an independent effort, so I would like to thank the Winter Park team, particularly Dr. Darcy Selenke and Jennifer Merten, RN, BSN, of the East Grand Community Clinic and Emergency Center for responding to my many data requests. I would also like to thank Winter Park Ski Patrol and Winter Park Resort management for supporting this endeavor.

Finally, I am thankful for the students, colleagues, and professors of the Department of Epidemiology who provided valuable education and insight, and fostered my growth in the field of public health.

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CHAPTER I

INTRODUCTION

Over 10 million people participate in skiing and snowboarding in the United States (U.S.) annually, including 500,000 Colorado residents. In total there are 50 million participant-visits to U.S. resorts annually.[1] Accordingly, an estimated 600,000 patients with skiing- or snowboarding-related injuries are treated in physicians' offices, emergency departments (EDs), and hospitals each year.[2] Serious yet common injuries such as traumatic brain injury and knee ligament ruptures have been shown to result in substantial personal and societal healthcare costs and in some cases lead to lifelong disability.[3-5] Every year approximately 40 skiers and snowboarders die due to traumatic injuries sustained inbounds at resorts during operating hours.[6] Targeting injury prevention to skiers and snowboarders could have significant impact on the morbidity, disability and mortality associated with participation, helping to achieve the Centers for Disease Control and Prevention Healthy People 2020 goal of reducing the sports-related injury burden by 10%.[7]

Injuries to skiers and snowboarders are a multifactorial and complex problem resulting from the contribution of and interplay between intrinsic and extrinsic factors.[8-11] Intrinsic factors are related to the individual and include demographics, skill level, and physiological factors. Extrinsic factors include equipment and the physical or social environment in which the injury occurs (weather, location on the mountain). Most prior research has investigated the relationship between intrinsic factors and injuries, but data sources have been subject to significant limitations. Such sources include tertiary care centers[12,13], which may underestimate the burden of injury and only include the most severe injuries; patient-self-report, which is subject to significant recall bias[14]; or ski patrol data, which are not based on physician diagnosis.[15,16]

Additionally, while prior studies have shown the most effective approaches for injury prevention are multifactorial, little research has been conducted on how environmental factors contribute alongside individual characteristics to influence skiing- and snowboarding-related injury patterns in the U.S. One largely untested assumption is that certain snow and weather conditions could lead to greater injury rates, increase the risk of injury, or influence the type of injury sustained.[9,17,18] An area of unexplored research is the effect of resort crowdedness on injury rates, mechanisms, and patterns.

This thesis is framed within the multi-factorial model of sports injury etiology developed by Meeuwisse in 1994 (**Figure 1**), which states that athletic injuries are the product of intrinsic factors, extrinsic factors, and an inciting event.[19] Intrinsic factors are specific to an individual and predispose an athlete to injury but are rarely themselves enough to cause an injury. Exposure to extrinsic factors, such as protective equipment and weather, further increases or decreases the athlete's susceptibility to injury. Finally, an inciting event (e.g., fall, collision) occurs and ultimately produces the injury, conditional upon the characteristics observed prior to the event. Based on this conceptual framework, multivariable approaches to modeling injury outcomes preferable over commonly used univariate approaches.[20] The goals of this research were to utilize established conceptual framework to enhance the understanding of injury etiology in skiing and snowboarding. Aim 1 explored intrinsic variables; Aim 2 explored extrinsic variables; and Aim 3 explored their relative contributions and interactions.

While prior studies have shown that the most effective approaches for injury prevention are multifactorial, there has been little research on the extent to which intrinsic and extrinsic factors contribute and interact to influence skiing- and snowboarding-related injury patterns in the U.S.[21] Efforts to quantify this relationship are warranted as they may translate into improved targeted prevention efforts. To address this challenge, retrospectively collected data on injured participants from a medical clinic located at the base of a popular Colorado ski resort, Winter Park Resort, were used to perform a comprehensive epidemiological evaluation of intrinsic and extrinsic factors and their effects on injury rates and patterns. Knowledge gained from this study has the potential to directly influence and inform targeted injury prevention campaigns, safety promotion at resorts, and on-hill first responder practices and resource allocation. The expected outcomes of this research are to 1) identify novel extrinsic factors and 2) determine the most influential factors (both intrinsic and extrinsic) related to injury rates and patterns among recreational skiers and snowboarders. Results from this study can be added to the evidence-base of injury prevention strategies that ultimately inform decision-making around skier and snowboarder safety in order to reduce the frequency and severity of skiing- and snowboarding-related injuries. The long-term goal is to reduce the substantial number of injuries sustained annually at U.S. ski resorts, although the findings may have implications that extend globally.

Specific aims and hypotheses

Specific aim 1

Aim 1 is to evaluate the effect of intrinsic factors on patterns of injury among recreational skiers and snowboarders. Hypothesis 1.1: Patterns of injury will vary by intrinsic factors. For example, males will sustain a greater proportion of fractures compared to females, while females will sustain a greater proportion of strains and sprains compared to males. Hypothesis 1.2: The relationship between intrinsic factors and patterns of injury will be modified by type of participation (skiing vs. snowboarding).

Specific aim 2

Aim 2 is to evaluate the role of extrinsic factors (subjective and objective weather and snow conditions, difficulty of trail run, number of other participants present at the resort, number of acres of open terrain, time of day, etc.) on patterns and rates of injury among recreational skiers and snowboarders. Hypothesis 2.1: Patterns of injury will vary by extrinsic factors. For example, the proportion of knee injuries compared to all other injuries will be greater on days with more snowfall, and the proportion of fractures will be greater on days with less snowfall. Hypothesis 2.2: The relationship between extrinsic factors and patterns of injury will be modified by type of participation (skiing vs. snowboarding). Hypothesis 2.3: There will be an inverse relationship between injury rates and a) snowfall; b) temperature; and c) visibility (e.g., decreased snowfall will lead to increased rates of injury). There will be a positive relationship between injury rates and participant density (i.e., a greater density of participants will be associated with increased injury rates).

Specific aim 3

Aim 3 is to evaluate how both intrinsic factors and extrinsic factors affect injury patterns among recreational skiers and snowboarders. Hypothesis 3.1: The relationship between the extrinsic factors and patterns of injury will be independent of significant intrinsic factors.

Significance

This research has the potential to advance the understanding of skiing- and snowboarding-related injuries by examining multiple associated potential risk factors. Further, it will produce novel findings on the relationship between extrinsic factors and injury, and also combine several sources of data rarely captured together into a comprehensive multivariable analysis. Utilization of data from a resort-side medical clinic at the base of the mountain enables capturing of most injuries in need of immediate medical care. While several studies have been conducted on injuries in winter sports, limitations in the field include weaknesses in sources of injury data, univariate analyses, and lack of evaluation of environmental factors.[22] The injury data to be used in this thesis are clinic-based, which is important because physician evaluation is the standard in injury diagnosis.[23] Using clinic data also avoids several potential problems encountered in previous studies. Only including injuries severe enough to present to EDs likely underestimates the true burden, using patient self-report risks recall and reporting bias (participants may not be able to accurately remember the event information), and ski patrol could misclassify injuries, resulting in skewed estimations of specific injuries.

The best approaches for injury prevention are multi-faceted and consider intrinsic and extrinsic factors. However personal behaviors can be difficult to change, making environmental modifications desirable to protect the largest number of people.[21] Although weather is non-modifiable, knowledge of the relationship between extrinsic factors and injury can influence many facets of on-hill safety practices. Primary prevention efforts could include placing simple warning signs at the top of ski lifts to encourage safe behaviors in sub-optimal conditions, grooming runs, redirecting flow of traffic to forcibly reduce speed on icy days, and altering of closing or opening times. Secondary prevention is possible through changing on-hill allocation of resources used in the care and management of injuries. In addition to weather considerations, increased resort crowdedness could affect the frequency of injury due to increased opportunity for collision yet remains untested. The data collected in this research can determine if the number of participants present on the hill per open acre of terrain, a modifiable condition, is associated with injury rates and patterns. This research is also the first to calculate daily injury rates to determine how weather affects injury risk.

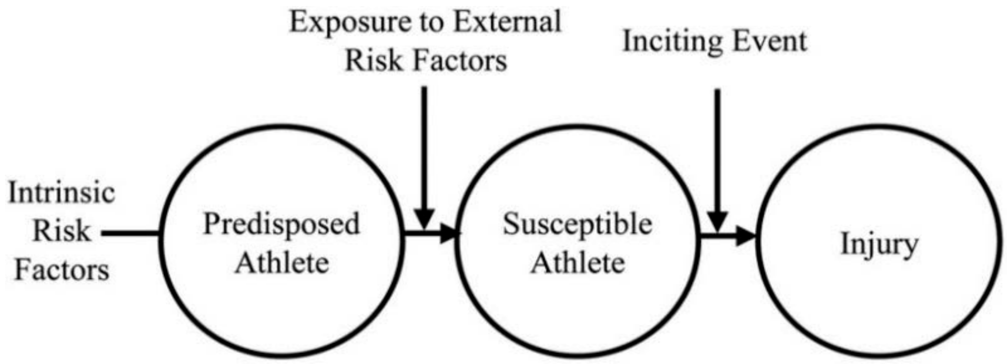


Figure 1. A multi-factorial model of sports injury etiology.

CHAPTER II

LITERATURE REVIEW

Burden of injury

Over 10 million people participate in the winter sports of skiing and snowboarding each year, amounting to more than 53 million visits to United States (U.S.) resorts in the 2015/16 season.[1] In 2013/14, 500,000 Colorado residents skied or snowboarded at least once, representing 9% of the state's population. Visits to Colorado ski resorts account for 24% of all U.S. skier visits, 5.6 million of which were from Colorado residents. Those who take part in skiing and snowboarding receive the numerous benefits associated with outdoor exercise including increased happiness and improved long-term health outcomes, but with participation comes risk for injury due to the inherent high-energy kinetics associated with the sports.[9,24,25] Consequently, up to 140,000 injuries due to skiing and snowboarding are treated in U.S. emergency departments (EDs) annually; estimates from 2002 showed 600,000 visits to physicians, EDs, and hospitals.[11,26]

Skiing has existed for thousands of years as a form of transportation, and recreational downhill skiing in the U.S. has existed since the early 1900s. Researchers became aware of the injury burden associated with skiing in the 1940s, and have worked ever since to develop prevention measures to decrease injury rates.[27] Early research calculating ski injury rates in the 1970s found an injury rate of 8 per 1,000 skier-days (one person participating in skiing for all or part of a day, generally based on lift ticket sales).[17,28] Fortunately overall rates have since declined from 3.1 per 1,000 skier-days in 1980 to 2.6 in 2000, mainly attributable to advances in equipment safety.[7] However, rates have remained virtually unchanged since, highlighting the need for continued and increased injury prevention efforts. Domestic and international studies using ski patrol report forms as their primary data source have reported rates between 1.4 and 6.1 per 1,000 participant-visits.[11,13,29-34] Snowboarding is a relatively young sport compared to skiing, rising in popularity during the 1980s and eventually becoming an Olympic sport in the 1998 Nagano, Japan games.[11,12] Injury rates among snowboarders are higher and more variable compared so skiing injury rates. One 20-year study of injuries using ski patrol reports forms found that in 1990 the injury rate was 3.3 per 1,000 snowboarder-days, rose to 7.0 in 2000, and has since declined to 6.1 in 2010.[7] The majority of the literature comparing skiers to snowboarders has shown that snowboarders have twice the rate of injuries than skiers, and that the two sports differ considerably in patterns of injury.[35-39]

Ski patrol report forms are the most common source of injury data, and capture more injuries than medical clinics, which likely explains why studies using ski patrol data report higher injury rates than those using clinic data.[37] Similarly, clinics capture more injuries than hospitals, emergency departments, or trauma centers.[16,38] Such evaluations of hospital-based data reported rates for skiers and snowboarders combined between 0.06 and 0.7 per 1,000 participant-visits, but included only the most severe injuries or specific injuries types (e.g., spinal cord injury).[38,40,41] When considering overall injury rates, it is important to evaluate the injury data source to accurately determine injury burden.

Patterns of injuries

Skiing and snowboarding have experienced dramatic changes in overall participation, demographics, and equipment over many decades resulting in substantial changes in injury patterns. For example, research during the 1970s showed a high proportion of lower leg fractures among skiers (>25% of injuries).[42] Evidence suggests that this was largely a product of the equipment available at the time.[43] Skis were not yet equipped with bindings that would release the boot from the ski in the event of a fall, resulting in an over-representation of mid-shaft tibia and fibula fractures.[44,45] Since the introduction of modern equipment (i.e., carving skis, releasable bindings), the incidence of leg fractures has decreased, but the risk of sustaining a knee sprain increased 240% between 1970 and the early 1990s.[42,43] Presently, common injuries seen in skiers are knee sprains, head injuries, and hand injuries (e.g., skiers thumb), although lower leg injuries are still common among children and those treated in emergency departments.[25,46,47] Similar to skiing, injury patterns among snowboarders have shifted over time. In 1990, ankle injuries comprised 22.4% of all snowboarding injuries, but only 3.1% in 2010.[7] This decrease was likely influenced by improvements in boot technology, similar to the effect of bindings on ski injuries.[48,49] Wrist injuries have consistently represented a large proportion of snowboarding injuries with estimates ranging from 20.2% in 1990 to 27.7% in 2011.[39] Taken together, studies conducted over the course of many years show that some injuries have remined consistent over time, yet others have experienced dramatic shifts, underscoring the need for systematic and continual collection of injury data.

Unfortunately, participation in skiing and snowboarding can result in serious injury. Head injuries, including traumatic brain injury (TBI), are a major concern in both sports, accounting for up to 20% of all ski- and snowboard-related visits to U.S. EDs.[26,46,50] TBIs have the potential to result in severe short- and long-term physical (i.e., inability to work or perform daily tasks), psychological disability (i.e., psychiatric illness, cognitive impairment) and death.[51-53] TBIs account for 50-88% of the ~40 ski and snowboarding deaths in the U.S. each year.[6] Further, skiing and snowboarding are among the top 10 sports contributing the most visits to U.S. EDs for head trauma in both the adult and pediatric populations.[54] In skiing, knee sprains are a major source of morbidity. Alpine skiers have the highest rates of anterior cruciate ligament (ACL) tears among popular recreational sports and account for up to 25% of all skiing injuries.[11,55,56] An ACL rupture can result in costly acute repair with surgery and rehabilitation, and lead to long term consequences such as early osteoarthritis.[4,57]

Intrinsic factors

Many epidemiological studies have been conducted to identify intrinsic risk factors associated with skiing and snowboarding-related injuries. While a consensus has been reached on many risk factors, some of the literature is equivocal. Most studies support the finding that snowboarders have higher rates of injury than skiers and males tend to be injured more frequently than females in both sports.[37,39,47,48,58] Young age (18-25 years old) and inexperience also appear to increase risk for injury, especially among snowboarders.[26,46,47,59,60] Although some studies of helmet use show no effect either on severity or overall risk of sustaining a head injury, the majority have shown that helmets reduce risk and advocate for the use of one while skiing or snowboarding.[22,35,61,62] Based on the strong empirical evidence, the American Pediatric Association endorses ski helmet use among children who ski or snowboard.[63] Residence also affects severity and behavior on the slopes. Girardi *et al.* found that non-local residents experienced more severe injuries than locals, and a recent study by Milan *et al.* on helmet use in Colorado children showed that Colorado residents were twice as likely to wear a helmet and less likely to sustain a severe injury than those visiting from out of state.[64,65] Some studies show that alcohol use is a risk factor in severity of injury, while others find no association.[12,66] Being in a lesson was protective in some studies, and harmful in others.[67]

Discrepancies in findings may exist due to different methodologies, data sources, and time periods covered. One common observation across studies, however, is that the environment likely plays a large role in the patterns of injury observed, yet weather and snow conditions are infrequently included. In fact, many studies list the exclusion of such variables as an analytic limitation and a necessary future direction.[12,18,22,38,47,62,67-69]

Extrinsic factors

A proposed but largely untested assumption between extrinsic factors (i.e., the external environment) and injury is that some weather or snow conditions could lead to greater injury rates, increase the risk of injury, or influence the type of injury sustained.[9] Few studies have addressed the potential effect of the environment, and have mostly relied on subjective measures of self-report of snow conditions. Two studies of the relationship between snowfall and ski and snowboard injuries found that increased 24-hour total snowfall was independently associated with a decrease in injury severity.[9,65] From a self-report survey, Hasler *et al.* found that subjective "bad" weather/visibility increased injury risk for both skiers and snowboarders as did skiing on old snow compared to new snow.[12] The same study showed that icy conditions may be a risk factor for snowboarders who sustain head injuries if they are not wearing a helmet. Another study found that knee injuries were more prevalent in female skiers at the lowest quartile of temperature but found no difference for males.[18] In addition to weather and slope conditions, the presence of other skiers and snowboarders on the hill could influence the likelihood of involvement in a collision resulting in injury, which have reported to be more severe than other mechanisms.[9,38,54] More participants may also influence the conditions of the slopes (i.e., scrape soft snow off, create moguls). A lone study conducted in 1991 asked injured participants about hill traffic, and reported that 59% of injured skiers reported "light traffic" with only 7% reporting "heavy traffic".[48] In summary, of the studies that included environmental conditions, few report on objective weather conditions in addition to subjective measurements, and it is unknown how the presence of other participants on the hill affects either the rate or type of injuries seen at ski resorts. **Table 2** summarizes peer-reviewed epidemiological studies of recreational skiers and snowboarders including weather- and snow condition-related factors evaluated in Chapters IV, V, and VI of this thesis.

Summary

Understanding intrinsic and extrinsic factors influencing injury rates and patterns is an important area of research. Little is known about environmental factors that influence overall injury risk or risk for specific injury. Further research exploring environmental factors in particular can inform more effective interventions aimed at large populations. This dissertation explored the influence of intrinsic and extrinsic factors on injury rates and patterns in a large sample of injured participants at one of the largest destination resorts in Colorado and the U.S., Winter Park Resort.

Table 2 Summary of peer-reviewed epidemiological studies of recreational skiers and snowboarders including weather- and snow condition-related factors evaluated in Chapters IV, V, and VI.

Author	Population, location, season	Data collection design	Extrinsic exposure(s)	Outcome	Method of data analysis	Main findings
Abu Laban *et al.*, 1991[48]	73 injured snowboarders treated in ED, Canada, 1988/89-1989/90	Descriptive epidemiology	Temperature, traffic, time of day	Injury proportion	Descriptive only	-49% of injuries occurred at 0 Celsius or above -57% occurred after 12 p.m. -7% reported heavy traffic at time of injury
Bouter *et al.*, 1989[17]	572 injured Dutch skiers and 576 controls, 1984/85	Case-control, insurance claims	Snow quality, visibility	Injury >1 day of missed work or skiing	Mantel-Haenszel adjusted (age and gender) odds ratio	-OR (95% CI) for icy spots vs. fresh snow = 1.4 (1.0-1.9) -OR (95% CI) for poor vs. good visibility: 0.4 (0.3-0.7)
Chow *et al.*, 1996[70]	797 skiers and snowboarders, rural ED, California, 1993/94	Descriptive epidemiology	Snow conditions	Injury proportion	Descriptive only	Snow conditions were packed-powder or icy in 82.5% of cases
Girardi *et al.*, 2010[65]	2,511 injured skiers and snowboarders treated in ED, Italy, 2002/03-2004/05	Descriptive epidemiology	Previous 24-hour snowfall	Injury severity score (ISS)	Spearman correlation	-Increased snowfall was associated with decreased ISS; r_s = -0.05, p = 0.009
Hasler *et al.*, 2009[71]	782 injured skiers treated at trauma centers, 496 non-injured controls, Switzerland, 2007/08	Case-control	Snow conditions	Injury	Multivariable logistic regression	-OR (95% CI) for fresh vs. old snow = 0.31 (0.12 – 0.80)
Hasler *et al.*, 2010[12]	306 injured snowboarders treated at trauma centers, 253 control snowboarders, Switzerland, 2007/08	Case-control	Bad weather/ visibility, snow conditions	Snowboarding-related injury	Multivariable logistic regression	-OR (95% CI) for bad vs. good weather/visibility = 19.06 (2.70 – 134.73). -OR (95% CI) for fresh vs. old snow = 0.20 (0.06 – 0.64)
Hume *et al.*, 2015[67]	N/A	Meta-analysis	Visibility	Injury	Pooled odds ratio estimates	-OR (95% CI) for bad vs. good visibility = 2.69 (1.43 – 5.07)

Table 2 continued. Summary of peer-reviewed epidemiological studies.						
Machold *et al.*, 2000[72]	2,579 snowboarders <18 years, school survey, Austria, 1996/97	Cross-sectional survey	Snow conditions	Injury rate per snowboarder day	Poisson regression	-IRR (95% CI) for icy vs. groomed snow = 3.04 (1.78-5.19) -IRR (95% CI) for hard vs. groomed snow = 4.91 (3.16-7.64)
Moore *et al.*, 2013[9]	644 skiers, level III trauma center, Vail CO, 2011/12	Descriptive epidemiology	Previous 24-hour snowfall	Injury severity score	Spearman correlation	-Increased snowfall was associated with decreased ISS: r_s = -0.08, p = 0.05
Ruedl *et al.*, 2011[69]	Female only, 93 cases, 93 uninjured controls, local ski clinic, Austria, 2006/07-2007/08	Case-control, matched on age	Skiing while snowing, snow conditions	ACL injury	Multivariable logistic regression	-OR (95% CI) for skiing during snowfall vs. no snowfall = 16.63 (1.8-152.1) -OR (95% CI) for skiing when icy vs. not icy = 24.33 (6.8-86.5)
Ruedl *et al.*, 2012[18]	1,039 knee injuries, 1,299 patients with other injuries, ski patrol clinics, Austria, 2008/09	Retrospective descriptive epidemiology	Skiing while snowing, quartiles of temperature	Knee injury	Prevalence comparisons	-Prevalence of knee injury was higher during snowfall (15.4% vs. 8.6%, p = 0.001) and in lowest temperature quartile compared to highest for females only (61% vs. 50%, p = 0.015).
Ruedl *et al.*, 2013[73]	2,326 injured skiers and snowboarders, 89.7% on slope, 10.3% at intersections, local ski clinic, Austria, 2010/11	Case-control	Mechanism of injury	Injuries sustained at intersections	Multivariable logistic regression	-OR (95% CI) for sustaining an injury due to a collision compared to fall = 2.0 (1.2 – 3.3) in intersections compared to open slopes
Russell *et al.*, 2014[16]	333 snowboarders injured in terrain parks, ski patrol and ED records, Canada, 2008/09-2009/10	Case-control	Groomed vs. not groomed snow	Presentation to ED, ski patrol, or both	Multinomial logistic regression	OR (95% CI) for groomed vs. not groomed snow = 0.24 (0.08-0.72). for presenting to ED vs. presenting to both ski patrol and ED
*Only studies that included extrinsic factors evaluated in this thesis are included. OR = odds ratio, IRR = injury rate ratio, CI = confidence interval, ISS = injury severity score, ED = emergency department.						

CHAPTER III

MATERIALS AND METHODS

Setting

This study was conducted at Winter Park Resort during the 2012/13-2016/17 ski seasons. Winter Park Resort is one of the largest destination ski resorts in the United States (U.S.) that receives nearly 1 million skier and snowboarder visits annually and comprises 3,081 acres of terrain, 25 chair lifts, and a has base elevation of 9,000 feet. Winter Park Resort is open to participants between 9:00 a.m.– 4:00 p.m. on weekdays and 8:30 a.m.– 4:00 p.m. on weekends. The East Grand Community Clinic and Emergency Center (referred to as the medical clinic) is a unique medical facility located directly at the base of Winter Park Resort. It is both a primary care/family medicine facility and Level 5 trauma center affiliated with the Denver Health and Hospitals Authority (DHHA) medical system. **Figure 3.1** displays a map of the Colorado front range area displaying the proximity of the clinic to Winter Park Resort, compared to other emergency medical facilities in the area. There are no other emergency medical services located within 20 miles of the resort. DHHA's medical clinic is affiliated with a Level I trauma center that is 65 miles away in a major metropolitan area (Denver) to which patients in need of further medical care or evaluation are transferred. The proximity of the clinic to Winter Park Resort makes it the most accessible facility for emergency medical treatment for injuries that occur at the resort.

Study population

The study population included skiers and snowboarders of all ages who were 1) injured at Winter Park Resort; 2) injured as the direct result of participation in skiing or snowboarding, and 3) treated at The East Grand Community Clinic and Emergency Center. Following injury on the hill, participants who could ski or snowboard down on their own seek medical care from Winter Park Resort Ski Patrol or go directly to the medical clinic. Injured participants unable to ski or snowboard down independently were taken down to the base of the hill in a toboggan by ski patrol. Participants first evaluated by ski patrol were triaged and transferred to the medical clinic for further treatment and diagnostics if deemed necessary. Winter Park Resort Ski Patrol is located in the same facility as the medical clinic making transfer of patients convenient.

Only injured patients ultimately presenting to the medical clinic who received a definitive diagnosis through physician evaluation and, if applicable, confirmatory tests (e.g., ultrasound, plain radiography) were included in the study. Patients who refused medical care, who were seen only by ski patrol, or who were not evaluated at the clinic were excluded. Further, only patients with traumatic injuries were included. Patients with environmental injuries (e.g., sunburns and frostbite) or illnesses (e.g., colds, altitude sickness) were excluded. Finally, patients injured during other activities such as sledding, tubing, cross country skiing, and snowmobiling were excluded, as were those who slipped/tripped/fell not while skiing or snowboarding (e.g., slipping on ice in the parking lot, tripping while wearing ski boots).

Data collection

All protocols and procedures were approved by the Colorado Multiple Institutions Review Board (#13-1730). Three main sources were used during data collection: The East Grand Community Clinic and Emergency Center, Winter Park Resort Ski Patrol, and Winter Park Resort management. **Figure 3.2** displays patient selection procedures and the final study population.

East Grand Community Clinic and Emergency Center data

Tables 3.1 – 3.3 show the variables collected from medical clinic records. Prior to data collection, a clinic log of all admissions (not only those related to skiing or snowboarding) was reviewed by a clinic physician and screened for trauma-related cases. Two researchers then independently performed a retrospective chart review on cases identified by the physician and manually entered information for patients meeting inclusion/exclusion criteria into an SPSS (V23) database created for this study. Researchers reviewed a total of 7,523 records and excluded 1,128 that were determined to be unrelated to skiing or snowboarding resulting in a sample size of 6,395. Six cases had neither sport marked as the primary activity (box checked for skiing/snowboarding-related, but sport not explicitly specified) and thus were excluded from analysis in Chapters IV and VI.

Standardized protocols for extracting information from clinic records were created to ensure consistency between researchers since extraction involved interpreting notes surrounding circumstances of injury. Both researchers extracted information from the first 50 cases of data collection, after which an initial interrater agreement analysis using Cohen's kappa was performed to determine if there were differences in data extraction between researchers. Any variables that had a kappa value <0.80 were reviewed and the protocol for data extraction updated to address discrepancies.[74]

Between 2012/13-2015/16, all clinic notes were handwritten and scanned into the DHHA semi-electronic health record (EHR) system, which was accessed remotely through a secure virtual private network. The scanned documents were reviewed individually for each eligible case. In the last week of the 2015/16 season, DHHA upgraded to a full EHR system during which the handwritten clinic notes were unable to be scanned into the system and are therefore unavailable for analysis. Starting in 2016/17, all data were available completely electronically via online queries. Each patient treated in the clinic was assigned a medical record number (MRN) linked to the patient, and an encounter ID (EID) linked to each injury event. The MRN allowed researchers to determine if a patient had more than one injury event over the course of the study period and the EID allowed for exclusion of any follow-up visits unrelated to the primary injury event. Patients injured in separate injury events during the study period were included in the dataset as distinct cases.

Patients included in the study could also sustain multiple injuries in one injury event. For each patient, all injuries in the patient record were entered into the database, but only the first listed diagnosis (the most clinically important in the physician's expert opinion) was used for analysis unless the patient sustained head trauma (excluding superficial injuries such as abrasions) or a fracture, in which case the head trauma or fracture was included. For example, if a patient sustained a wrist fracture and a wrist contusion, the wrist fracture was used for analysis. If the patient sustained head trauma and a fracture, head trauma was included as the primary injury for analysis. Unclear injury diagnoses were reviewed by a physician practicing at the clinic for categorization. An example of an unclear diagnosis is "knee injury" in which no specific diagnosis was noted. **Table 3.1** displays the list of body part and diagnosis information collected. In addition to injury information, demographic information (e.g., age, gender), injury event information (e.g., mechanism of injury, helmet use), and injury outcome information (e.g., transferred to hospital) were collected. **Tables 3.2 and 3.3** display independent variables collected from clinic data.

After completion of data collection, a second agreement analysis was performed on 50 randomly selected cases (1% of the 2012/13-2015/16 data) to assess final inter-rater reliability for primary exposures and outcomes. All variables included in the final dataset had good (>0.60) or excellent (>0.80) agreement.

Winter Park Resort Ski Patrol

Additional information was collected on the patients evaluated by ski patrol prior to the clinic. **Tables 3.2 and 3.3** display variables collected from ski patrol. Ski patrol records were provided by Winter Park Resort and included date of evaluation, the patients' ability, last name, rental gear use at the time of injury, and the location code for where the injury occurred on the mountain. Injury diagnoses and body regions were also provided, but not used for analysis as physician diagnosis was considered the most accurate. Ski patrol information was not obtained for patients who bypassed ski patrol and presented directly at the resort-side clinic.

To obtain difficulty of run, the location code provided by patrol was matched to a ski patrol code sheet that provided the name of the ski run. The name of the run then was merged with difficulty of run (e.g., green, blue) obtained from information published on Winter Park Resort's website.[75]

Winter Park Resort

Winter Park Resort management provided historical environmental conditions and attendance information for each operating day for the 2012/13-2016/17 seasons. Daily snowfall was measured in inches by ski patrol at 5:30 a.m. using a snow stake (a specialized ruler) located within a SNOTEL (<u>sno</u>wpack <u>tel</u>emetry) site at the resort. SNOTEL sites are weather stations that also measure snow depth via pressure-sensing snow pillows and precipitation gauges. Attendance (number of unique scanned tickets or passes), open acreage, snow base depth (inches), and low and high temperatures (Fahrenheit, F) were provided in Excel spreadsheets.

For the 2013/14 and 2014/15 seasons only, visibility and snow condition information were additionally provided. Visibility and snow condition information were measured by the resort and condensed into a summary measure for each day (e.g., partly clear, packed powder). **Table 3.3** displays variables collected from resort management.

Record linkage and data merging

Standard record numbers linking clinic and ski patrol data were not provided by the Winter Park resort. Clinic and ski patrol data was merged using a unique ID created for each subject by combining the patient's last name and date of injury. Patients with the same last name whom were injured on the same date required further review before matching. Resort data was linked to the injury dataset by date. For protection of patient confidentiality, patient names were removed from the dataset and a password protected crosswalk (a system linking the patient ID to their record) was created for reidentification for future studies. A separate deidentified dataset with environmental variables and injury counts aggregated daily was created for modeling injury rates.

Study measures

Dependent variables

Primary outcome measures included mechanism of injury, body part injured, diagnosis, and disposition for all specific aims (**Table 3.1**). Mechanism of injury, body part injured, and injury diagnosis had more than 10 categories and were therefore categorized. Leaving outcomes as collected would not be feasible for the proposed analyses because 1) the statistical models with excessive categories would likely not converge due to small cell sizes and 2) increased numbers of categories decrease interpretability of results (in multinomial logistic regression, results are interpreted as contrasts between outcome categories, described in the following analysis section). Therefore, outcomes were collapsed into no more than 5 categories. Final categorization of outcomes considered distributions and collaboration with a physician to determine clinical relevance of comparisons.

Mechanism of injury was categorized into falls, collisions (two or more participants colliding), contact with objects (man-made and natural), and non-contact. Falls from chair lift, both entering/exiting and from height, were recategorized into the broader fall category and contact with lift was categorized as contact with an object. This categorization necessitated from perfect separation issues in the data, as the extrinsic variable of difficulty of run had a lift category that perfectly predicted the lift category in mechanism of injury.

Body parts injured were categorized into four body regions: head/face/neck, upper extremity, trunk, and lower extremity. Injury diagnoses were categorized into fractures, head trauma, sprains/strains, superficial injuries (contusions, abrasions, lacerations), internal injuries, dislocations/separations (including subluxations), and other injuries. The "other" diagnosis category was small (<1% of the data) and excluded for analysis in Chapter VI. Head trauma comprised concussions, closed head injuries, and other traumatic head injuries (excluding superficial injuries such as contusions, abrasions, lacerations). Internal chest injuries (e.g., pneumothorax, myocardial contusion, flail chest), excluding uncomplicated rib fractures and internal abdominal injuries (e.g., spleen laceration), were categorized as internal injuries.

Disposition was categorized into transferred or discharged home. Transferred patients included those sent to another medical facility via ambulance or helicopter, and those instructed by the clinic physician to seek further care but chose to transfer themselves in a personal occupancy vehicle (POV). It was not possible to verify if discharged POV patients truly sought further medical care, despite physician instructions.

Injury rates per 1,000 participant-visits were an additional primary outcome measure for specific aim 2.2. Injury counts were aggregated daily and divided by daily attendance numbers provided by the resort. The unit of exposure was a participant-visit, corresponding to one unique scanned ticket or pass. Specific types of injury rates were calculated (e.g., rate of fractures, rate of collisions) per 1,000 participant visits.

Intrinsic independent variables

Table 3.2 shows intrinsic independent variables of gender, age, residence, and the corresponding data source. Some variables were computed from others or categorized for interpretation, for comparison to prior research, or because leaving them as continuous would violate corresponding statistical model assumptions. Age was categorized into <15, 15-24, 25-34, 35-49, 50-64, and 65+ age groups based on the univariate age distribution and for interpretation of results. Continuous age also did not demonstrate linear relationships between the log odds of any outcome variable. Residence was computed from zip code and classified as in-state (i.e., from Colorado), out-of-state, or foreign. Out-of-state participants demonstrated similar injury patterns as foreign participants and were combined for analysis.

Extrinsic independent variables

Table 3.3 shows the corresponding data sources and their operationalization. Extrinsic variables of interest included sport, helmet use, equipment ownership, difficulty of slope, attendance, open resort acreage, participant density, snowfall, snow base depth, and temperature. Attendance was categorized based on median attendance. Participant-density, a novel measure of resort crowdedness, was computed as the number of participant-visits divided by the number of open acres on a given day and categorized into the top 10% of days compared to the bottom 90%. Snowfall was categorized into <1 inch and ≥1 inch[9] and temperature (average of high and low) was divided into quartiles for comparison to prior research and interpretability.[18] Time of day was dichotomized into before 12:30 p.m. and 12:30 p.m. or later. Snow conditions were classified by the resort as powder, powder/packed powder (mixture of powder and packed snow), packed powder, hardpack (firm snow surface), machine-made (blown early season to increase base depth), and spring conditions (variable due to nighttime freezing and subsequent daytime melting). Visibility was classified by the resort as clear, mostly clear, partly cloudy, mostly cloudy and cloudy.

Other variables

Season, month, and weekends/holidays compared to regular weekdays were additionally evaluated as potential confounders. In the temporal sequence of events leading to injury, the inciting event (e.g., collision, fall) precedes other injury outcomes, and the actual injury sustained (body region, diagnosis) may affect disposition.[19] Therefore, for models of body region and diagnosis, mechanism of injury was evaluated as a potential covariate. Similarly, mechanism of injury, body region, and diagnosis were evaluated as potential covariates for disposition.

Analysis

There were two primary methods used for analysis, logistic regression and negative binomial regression. Binary logistic regression was used to model the outcome of transferred compared to discharged home, and multinomial logistic regression was used to evaluate the association between predictors of interest and the nominal outcomes of mechanism of injury, body region injured, and injury diagnosis. Negative binomial regression was used to evaluate the relationship between environmental characteristics and injury rates.

Logistic and multinomial logistic regression.

Logistic regression was used to assess the relationship between a binary outcome (disposition) and one or more explanatory variables by modeling the odds or probability of an event using maximum likelihood estimation techniques. Odds ratios (ORs) and 95% CIs were calculated by exponentiating the beta coefficients in the logit model. The assumptions of logistic regression include a dichotomous outcome, independent observations, linearity between the logit function and continuous independent variables, and that independent variables are not linear combinations of one another. In this study there was not true independence of observations since a patient could be counted more than once in the dataset. However, less than 2% of the data included patients who were injured multiple times during the data collection period, so observations were treated as independent to meet the independence assumption. Continuous independent variables were categorized if they were not linearly associated with the log odds of being transferred. Multicollinearity between independent variables was assessed by computing Spearman or Pearson correlations, depending on the variable distribution, and by modeling each outcome using linear regression to obtain variance inflation factors (VIF).[76,77] If two independent variables had correlations >0.80 or a VIF>5, the variable most strongly associated with the outcome was included.

Multinomial logistic regression is an extension of the traditional logit model used with nominal outcome measurements. For this study, nominal outcomes included mechanism of injury, body part injured, and injury diagnosis. The interpretation of multinomial logistic regression can be difficult and requires careful selection of reference groups. Multinomial logistic regression cannot be interpreted as the probability of being in one category (as in logistic regression), and instead is most logically interpreted as contrasts between pairs of categories. As the number of categories in an outcome variable increases, so does the difficulty of interpreting the results. For example, the outcome of mechanism of injury has four categories, which corresponds to 6 possible comparisons or interpretations. For diagnosis, there are 15 possible comparisons. For the current analysis. falls were chosen as the reference category for mechanism of injury as the largest and most logical comparison group. Reference category choice for body region and diagnosis was less intuitive. The head/face/neck for body region and head trauma for diagnosis were ultimately chosen as head injuries are major concerns across diverse groups including participants, parents of young participants, clinicians and resorts.[22,64,78]

In addition to the assumptions of logistic regression, multinomial regression has the assumption of independence among the dependent variable choices. In other words, excluding an outcome category should not have a strong influence on the observed association. This assumption was assessed by modeling pairs of outcomes separately (e.g., collisions vs. falls only, non-contact vs. falls only) and comparing findings. As with logistic regression, ORs and 95% CIs can be estimated.

Negative binomial regression

Poisson regression is a method used to model dependent variables that have non-negative integer values, as with injury counts. An assumption of the Poisson distribution is that its variance must equal its mean. This assumption is rarely met in practice; often heterogeneity in the data results in a variance greater than the mean, resulting in overdispersion of the data. The negative binomial is a generalization of Poisson regression which includes an additional disturbance term to account for overdispersion. When it is necessary to include units of exposure, as in this study with participant-visits, the variable containing exposure information can be entered into the model.

General approach

Analyses specific to each aim are presented in Chapters IV, V, and VI. Means and standard deviations were used to describe continuous variables, and frequencies and percentages to describe categorical variables. The bivariate associations between intrinsic factors, sport, and outcomes were assessed using independent t-tests for continuous variables and Pearson chi-square for categorical variables. Cramer's V were computed to assess the magnitude of association between categorical variables.

To create each multivariable model, explanatory variables associated with the outcomes of interest ($p<0.20$) were included in a preliminary multivariable model. Any variable not selected for the initial model was added in individually and tested for significance and confounding. Variables were retained if any other parameter estimate changed >15%, regardless of the p-value for the confounding variable. This process determined if any variables not univariately associated with the outcome significantly influenced the results in the presence of other variables.[79] Finally, ORs or injury rate ratios (IRRs) with 95% confidence intervals were computed. Results were considered statistically significant if the 95% confidence interval for the OR or IRR did not contain 1.00. Building upon the final multivariable model, the presence of effect modification by sport was assessed by testing for statistical interactions between activity and other intrinsic factors. To be a significant effect modifier, the corresponding interaction term required a p-value <0.05.

Missing data and multiple imputation

Missing data can be a major source of bias in epidemiological studies. Most statistical software programs will automatically run complete case analyses (delete any cases with missing data for the variables in the model), which can lead to small analytic sample sizes but more importantly result in misleading findings depending on the type of missing data observed. Missing data can be missing completely at random (MCAR), missing at random (MAR) or missing not at random (MNAR). Listwise deletion is appropriate only if the data are MCAR and will not introduce bias into the findings. However, the assumption of MCAR is impossible to verify empirically as it assumes that the probability of missingness is not dependent on any variables, observed or unobserved. A more reasonable assumption is MAR, in which the probability of missingness is dependent upon other observed variables, but the missingness does not depend on the true (unobserved) values of the missing variable itself.[80] MNAR assumes missingness is dependent on the unobserved values of the missing variable.

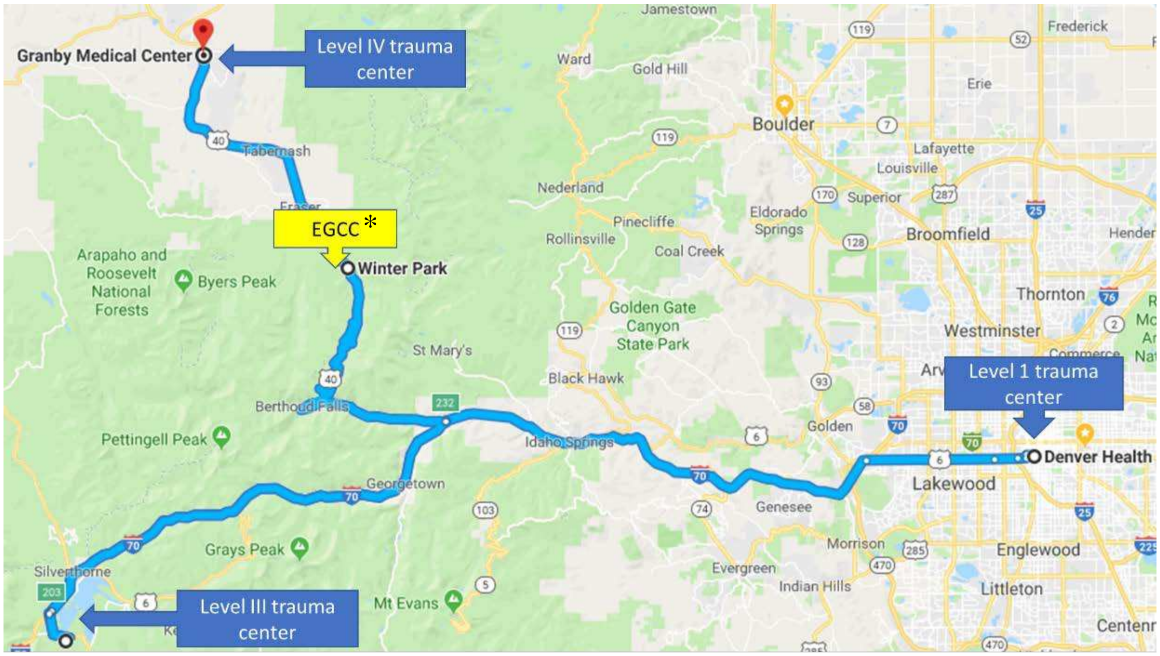
In this study, missing data arose from two main sources: chart information and ski patrol records. From 2012/13-2015/16, data were collected via retrospective chart review of handwritten notes scanned into the clinic EHR. There were several different forms that were used to fill out information, and clinicians often used different forms out of preference or because of their role at the clinic (e.g., nurse, doctor). Some clinicians did not use any forms, opting to write a SOAP (subjective, objective, assessment, and plan) note, a written method of documentation of patient interactions and treatment plans. The heterogeneity of forms used by providers resulted in missing information. For example, some forms had checkboxes for helmet use (Yes or No) while others did not, meaning that the clinician filling out the form without a checkbox would have to explicitly document helmet use in the notes section. The clinician may have been less likely to document this information if a patient had a leg injury compared to a head injury. This resulted in 8.6% missingness for helmet use, but <2% of missingness for any other variable recorded from clinic data. The other major source of missingness arose from ski patrol data. Ski patrol did not collect information on patients who bypassed patrol and sought care directly at the medical clinic. Thus there were substantial amounts of missing data for use of rented/borrowed equipment (18.0%), ability level (14.0%), and difficulty of run (12.6%). Altogether, missingness amounted to a complete case dataset of 75.6% (24.4% rate of missing information).

For this study the data were assumed to be MAR, and multiple imputation was chosen to account for the missing covariate data. Multiple imputation consists of three main steps: 1) imputation of the missing values multiple times; 2) analysis of each of the imputed datasets separately; 3) combining the parameter estimates from each imputation into a single estimate. Fully conditional specification (FCS) was chosen as the method of imputation since the dataset with which the imputations are performed consisted of a mixture of categorical and continuous covariates, and FCS does not rely on the assumption of multivariate normality.[81] Thirty imputations were run to achieve maximum relative efficiency for the total amount of missingness (24.4%).[82] Finally, models using listwise deletion and the imputed data sets were compared. Since the results were similar, Aim 3 presents results from the multiple imputation analysis.

Power

Techniques for binomial logistic regression were used since a multinomial regression can be interpreted as a series of binomial logistic regressions and no clear method exists for multinomial regression. The following sample power calculation was performed in G*Power 3 (v3.1) and estimated the sample size necessary to detect an effect of activity on the odds of sustaining a head injury compared to all other injuries.[83] Assuming 80% power, 55% of patients are snowboarders[22], and that 10% of injuries to snowboarders are to the head, a total sample size of 1,861 was needed to detect an odds ratio of 1.50.[12,84] When controlling for other moderately correlated covariates, a sample size of 2481 will be needed. **Figure 3.3** shows the ranges of sample sizes needed to detect a range of odds ratios for various levels of power. The sample size of 6,395 in this study assured adequate power.

The power calculation for the negative binomial regression estimates the sample size necessary to detect a 50% increase in injuries on days with >1 inch of snowfall compared to days with ≥1 inch of snowfall.[9] Assuming 80% power, a baseline rate of injury of 2.5 per 1,000 participant-days, snowfall of <1 inch on 20% of days, and the presence of other moderately correlated covariates, to detect a 50% increase in injuries on days with <1 inch of snow, 187,182 participant-days was needed. **Figure 3.4** shows the ranges of sample sizes needed to detect a range of changes in rates for various levels of power. Winter Park Resort receives nearly 1 million visits per year, ensuring adequate power to detect meaningful effect sizes.



*EGCC = East Grand Community Clinic and Emergency Center

Figure 3.1 Map of select major trauma centers within driving distance of Winter Park Resort, Colorado.

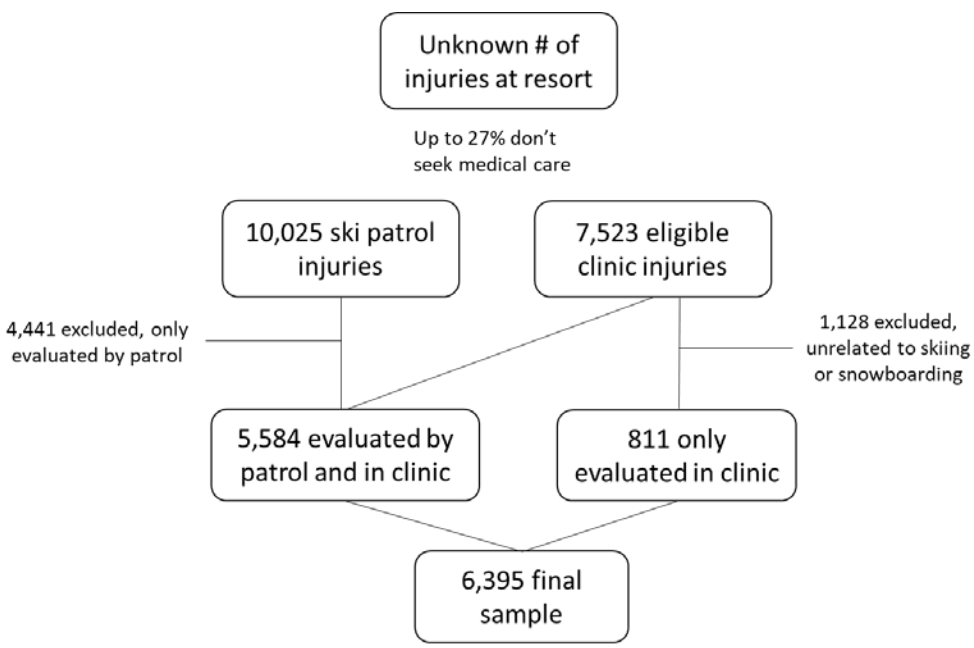


Figure 3.2 Patient selection and final study population.

Table 3.1 Outcome variables collected from the Winter Park Resort medical clinic, Winter Park Resort 2012/13-2016/17 seasons[a].

Mechanism of injury	Body part		Diagnosis	Disposition
Fall to snow[b]	Head/face[d]	Sternoclavicular joint[e]	Fracture	Discharged home
Contact with natural object[c]	Eyes[d]	Hand/finger[e]	Head trauma	Ambulance transfer[k]
Contact with manmade object[c]	Mouth/teeth[d]	Ribs/sternum[f]	Ligament sprain[h]	Air transfer[k]
Contact with another person	Ears[d]	Upper back/t-spine[f]	Muscle strain[h]	POV[k]
Contact with own equipment[c]	Neck/C-spine[d]	Abdomen[f]	Tendon strain[h]	Other transfer[k]
Non-contact	Clavicle[e]	Pelvis/sacrum[f]	Cartilage injury[h]	
Fall entering/exiting liftt[b]	Shoulder[e]	Hip/groin[g]	Contusion[i]	
Fall from lift from height[b]	Upper arm[e]	Thigh/hamstring[g]	Laceration[i]	
Struck by lift[c]	Elbow[e]	Knee[g]	Dislocation[j]	
Stuck by moving vehicle[c]	Forearm[e]	Lower leg[g]	Subluxation/ Separation[j]	
Other	Wrist[e]	Ankle[g]		
	Acromio-clavicular joint[e]	Foot/toe[g]	Abrasion[i]	
		Other	Internal injury	
			Other	

a. Letter superscripts indicate categorization of dependent variables for analysis. b. Falls c. Contact with objects d. Head/face/neck e. Upper extremity f. Trunk g. Lower extremity h. Sprain/strain i. Superficial injury j. Dislocation/separation k. Transferred. POV = personal occupancy vehicle. Injuries initially marked as other were reviewed for final categorization.

Table 3.2 Intrinsic variables and corresponding data sources, Winter Park Resort, 2012/13-2016/17 seasons.

Intrinsic Variable	**Original distribution**	**Operationalization (if different from original distribution)**	**Source**
Sex	Male Female	-	Clinic
Age (years)	Continuous	<15 15-24 25-34 35-49 50-64 65+	Clinic
Zip code	Nominal	In-state Out-of-state Foreign	Clinic
Ability	Beginner Intermediate Advanced Expert	-	Ski patrol

Table 3.3 Extrinsic variables and corresponding data sources, Winter Park Resort, 2012/13-2016/17 seasons[a].			
Extrinsic variables	**Original distribution**	**Operationalization (if different from original distribution)**	**Source**
Sport	Skier Snowboarder		Clinic
Helmet use	Yes No		Clinic
Equipment ownership	Owned Rented or borrowed		Ski patrol
Difficulty of slope	Green (Beginner) Blue (Intermediate) Blue/black (Intermediate/advanced) Black (Advanced) Double black (Expert) Terrain park Lift	Black and double black combined	Ski patrol
Injury date	Ordinal		Clinic
Time of injury	Continuous	Before 12:30 p.m. 12:30 p.m. or later	Clinic
Attendance (participant-visits)	Continuous	≥ median < median	Resort
Open acres	Continuous	Percent open acreage	Resort
Participant density (participants/acre)	Continuous	≥ 90th percentile < 90th percentile	Computed from attendance and acres
Snowfall (inches)	Continuous	≥ 1 inch < 1 inch	Resort
Snow base depth (inches)	Continuous		Resort
Low temperature (F)	Continuous	Average temperature divided into quartiles	Resort
High temperature (F)	Continuous		Resort
Snow conditions[a]	Powder Powder/packed powder Packed powder Hardpack Machine made Spring		Resort
Visibility[a]	Clear Mostly clear Partly cloudy Mostly cloudy Cloudy		Resort
a. Information obtained only for the 2013/14 and 2014/15 seasons.			

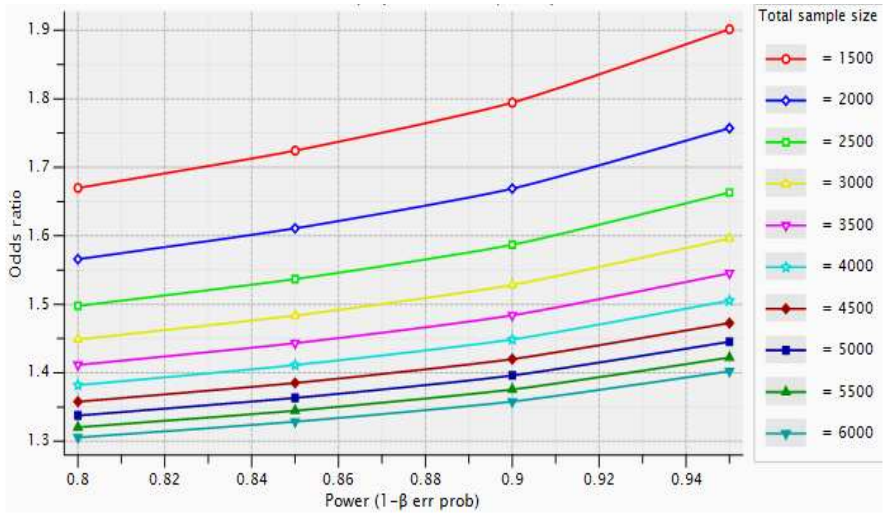


Figure 3.3 Power analysis for logistic regression using G*Power 3.[83]

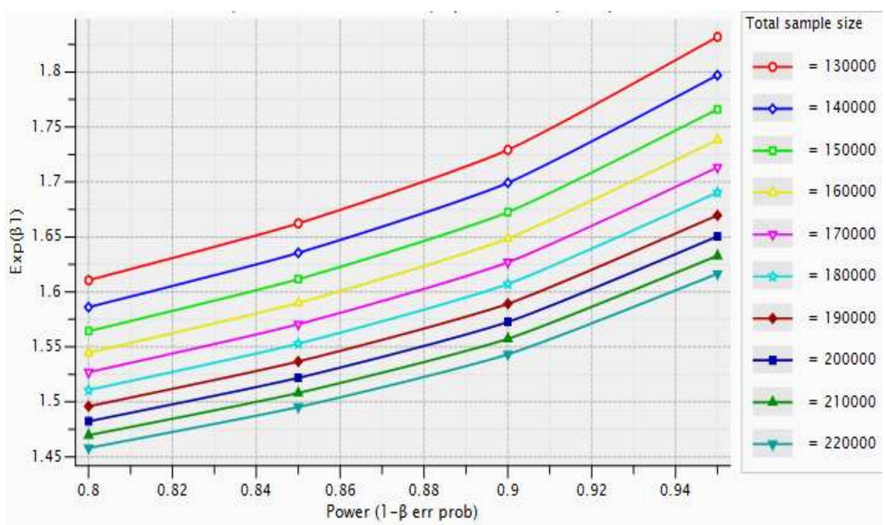


Figure 3.4 Power analysis for negative binomial regression using G*Power 3.[83]

CHAPTER IV

A COMPARISON OF RECREATIONAL SKIING- AND SNOWBOARDING-RELATED INJURIES AT A COLORADO SKI RESORT

Abstract

Objective: To describe and compare injury patterns between recreational skiers and snowboarders at a Colorado ski resort. Design: Retrospective descriptive epidemiology of an injured patient cohort. Setting: A mountainside medical clinic (level V trauma center). Patients: Injured skiers (n=3,961) and snowboarders (n=2,428) presenting to the clinic between 2012/13-2016/17. Independent variables: Sport (skiers compared to snowboarders). Main outcome measures: Demographics/characteristics (age, sex, ability, helmet use), injury event information (slope difficulty, injury mechanism), and injury information (body site, diagnosis, disposition). Results: Skiers were older (34.3±19.3 years) than snowboarders (23.2±10.5 years, $p<0.001$) and a greater proportion of skiers were female (46.3%) compared to snowboarders (27.8%, $p<0.001$). A similar proportion of skiers (84.4%) and snowboarders (84.5%) were helmeted ($p=0.93$). Ability level, slope difficulty, and injury mechanism differed between sports ($p<0.001$ each). Snowboarders were most frequently beginners (38.9%) while skiers were intermediates (37.8%). Falls to snow (skiers=72.3%, snowboarders=84.8%) and collisions with natural objects (skiers=9.7%, snowboarders=7.4%) were common injury mechanisms. Over 60% of skiing and snowboarding injuries occurred on beginner or intermediate slopes; 16.1% of snowboarding injuries and 6.1% of skiing injuries occurred in terrain parks. Common skiing injuries were knee sprains (20.5%) and head trauma (8.9%); common snowboarding injuries were wrist fractures (25.7%), shoulder separations (9.1%), and head trauma (9.0%). A greater proportion of skiers were transferred to another medical facility (9.9%) compared to snowboarders (7.1%, $p<0.001$).

Conclusion: Injury patterns differed between sports. It is important for clinicians, ski patrollers, and resorts to develop and deliver sport-specific injury prevention interventions to most effectively decrease injury burden.

Introduction

Skiing and snowboarding are popular winter sports with millions of participants worldwide.[85,86] Though many differences exist between the sports including demographics, equipment, and skill, participation in either carries risk of traumatic injury that can result in short- and long-term physical, psychological, and financial hardship.[87,88] Increased understanding of injuries in this winter sport population is important for informing injury prevention efforts to reduce frequency, severity, and associated burdens.

While many studies have reported on differences in injury patterns between skiers and snowboarders, most rely on injury data from self-report, ski patrols, or tertiary trauma centers.[39,47,65,87,89] Mountainside clinic data are also important to use in the comprehensive study of injuries. Clinics treat injuries that may require more advanced care or diagnostics than provided by ski patrols, while still capturing less severe injuries that may not present to hospitals or emergency departments.[16,39,90] Further, many frequently cited studies were conducted over a decade ago and may not reflect the changing demographics (e.g., increasing population of older skiers, increased population of snowboarding) and equipment (e.g., changes in the shape of skis and boards) used by skiers and snowboarders.[26,31,48,90,91]

The purpose of this study was to describe and compare injury patterns between skiers and snowboarders during the 2012/13-2016/17 seasons at Winter Park Resort, CO. We also evaluated differences between sports in age, sex, ability, and factors such as helmet use, injury mechanism, and slope difficulty. Finally, we investigated injuries resulting in transfer to another medical facility for further evaluation.

Methods

Setting and study population

This retrospective descriptive epidemiological study was conducted at Winter Park Resort during the 2012/13–2016/17 ski seasons. The study population included people injured at Winter Park Resort while skiing or snowboarding and who received evaluation at a medical clinic (a level V trauma center and community clinic) located at the base of the resort. Individuals injured on the mountain and not independently mobile were brought down via toboggan by ski patrol, triaged, and transferred to the clinic for further evaluation and diagnostics if deemed necessary. Individuals who could ski or snowboard down independently either first presented to ski patrol and were triaged similarly or presented to the clinic directly.

Only injured patients ultimately presenting to the clinic who received a definitive diagnosis through physician evaluation and, if applicable, confirmatory tests (e.g., ultrasound, plain radiography) were included. Patients who refused medical care, who were seen only by ski patrol, or who were not evaluated at the clinic were excluded. Further, only patients with musculoskeletal or internal organ injuries were included. Patients with environmental injuries (e.g., sunburns and frostbite) or illnesses (e.g., colds, altitude sickness) were excluded. Also, patients injured during other activities such as sledding, tubing, cross country skiing, and snowmobiling were excluded, as were those who slipped/tripped/fell not while skiing or snowboarding (e.g., slipping on ice in the parking lot).

Data collection

All protocols and procedures were approved by the Colorado Multiple Institutions Review Board. Injury information was collected from the clinic via retrospective medical chart review. For the 2012/13-2015/16 seasons, two research assistants reviewed hand-written clinic notes that were scanned into a semi-electronic health record system (EHR). In 2016/17, Winter Park Resort upgraded to a full EHR, making data available through online queries. Occasionally, unclear injury diagnoses were reviewed by a physician practicing at the clinic for categorization. If a patient sustained multiple injuries, the first listed diagnosis (the most clinically important in the physician's opinion) was used for analysis unless the patient sustained head trauma (excluding superficial injuries such as abrasions) or a fracture. If the patient sustained head trauma and a fracture, head trauma was included for analysis and the fracture marked as a secondary injury. Each clinic patient had a medical record ID linked to the individual and an encounter ID linked to each visit, allowing researchers to exclude follow-up visits that were not the primary injury event.

In addition to injury information, age, sex, residence (Colorado vs. out-of-state or foreign), helmet use, injury mechanism, and disposition were obtained from clinic records. Self-reported ability level, slope difficulty on which the injury occurred, and use of rented/borrowed vs. owned equipment were collected from ski patrol records. Ski patrol information was obtained only for patients who were first evaluated by ski patrol, this information was not available for patients presenting only to the clinic.

Some variables were categorized for analysis. Concussions, closed head injuries, or head trauma (excluding superficial injuries such as contusions, abrasions, lacerations) were categorized as head trauma. Internal chest injuries excluding uncomplicated rib fractures were categorized as blunt chest trauma (e.g., pneumothorax, myocardial contusion, flail chest).

Internal abdominal injuries (e.g., spleen laceration) were categorized as blunt abdominal trauma. Lower leg fractures included only proximal or mid-shaft tibial or fibular fractures. Ankle fractures included distal tibial or fibular fractures. Tibial plateau fractures were categorized separately. Disposition was categorized as transferred to another facility or discharged home. Transferred patients included those sent to another medical facility via ambulance or helicopter, and those instructed to seek immediate further medical care but who chose to transport themselves.

Analysis

All analyses were performed in SAS V9.4 (Cary, NC). Prior to analysis, data were inspected for quality, normality, and missingness. Clinic records from the last week of 2015/16 were not scanned into the EHR and therefore unavailable. Means and standard deviations were calculated for continuous variables and frequencies and percentages for categorical variables. Statistical comparisons between skiers and snowboarders were made using independent t-tests for continuous variables, and Pearson chi-square for categorical variables with Cramer's V presented for effect size. Cochran-Armitage tests were used to evaluate linear changes in proportions of helmet use over time. P-values <0.05 were considered statistically significant (α level=0.05).

Results

Researchers reviewed a total of 7,523 records and excluded 1,128 for being unrelated to skiing or snowboarding. An additional 6 were excluded for having neither sport marked as the primary activity (box checked for skiing/snowboarding-related, but sport not explicitly specified). The final sample included 3,961 skiers (62.0%) and 2,428 (38.0%) snowboarders evaluated in the clinic during the 2012/13-2016/17 seasons.

Demographic factors

Table 4.1 compares demographic information for injured skiers and snowboarders. Most participants first presented to ski patrol (87.4% for both skiers and snowboarders) before evaluation in the clinic; the remainder presented directly to the clinic. Skiers were older than snowboarders (34.3±19.3 vs. 23.2±10.5 years, respectively, $p<0.001$). Compared to snowboarders, a greater proportion of skiers were female, out-of-state or foreign residents, and using rented or borrowed equipment (see **Table 4.1** for comparisons). Ability differed between sports ($p<0.001$); 25.5% of skiers were self-reported beginners compared to 38.9% of snowboarders. Conversely 8.7% of snowboarders were self-reported experts compared to 16.5% of skiers. A similar proportion of skiers (84.4%) and snowboarders (84.5%) wore a helmet at the time of injury ($p=0.93$). **Figure 4.1** shows changes in helmet use over time; the proportion of injured skiers wearing helmets increased from 75.2% in 2012/13 to 89.3% in 2016/17 ($p<0.001$). The proportion of injured snowboarders wearing helmets also increased from 78.4% in 2012/13 to 87.8% in 2016/17 ($p<0.001$).

Injury event

Table 4.2 displays distributions of slope difficulty, injury mechanism, and disposition (all differing significantly between sports, $p<0.001$). Skiers were most frequently injured on green/easiest slopes and blue/intermediate slopes (31.7% each); few occurred in terrain parks (6.1%). Snowboarders were also most frequently injured on green/easiest slopes (43.4%), blue/intermediate slopes (21.3%) but more often in terrain parks (16.1%). Falling to snow was the most common injury mechanism for skiers (72.3%) and snowboarders (84.8%) followed by collision with a natural object (9.7% for skiers, 7.4% for snowboarders). Collisions with other participants accounted for 6.2% of skiing and 2.6% of snowboarding injuries. A greater proportion of skiers were transferred to another medical facility (9.9%) compared to snowboarders (7.1%, $p<0.001$).

Injured body parts and diagnoses

Figure 4.2 displays proportions of injured body regions and diagnoses by sport. Skiers most commonly injured their lower extremities (46.1%) and sustained sprains/strains (33.9%), while snowboarders most commonly injured their upper extremities (62.3%) and sustained fractures (45.6%). **Table 4.3** displays the top 10 most common specific injury diagnoses for each sport. Knee ligament sprains (including grades I, II, and III) accounted for 20.5% of ski injuries, followed by head trauma (8.9%) and clavicle fractures (4.5%). Wrist fractures accounted for 25.7% of snowboarding injuries, followed by shoulder separations (9.1%) and head trauma (9.0%).

Injuries resulting in transfer

Table 4.4 shows specific injuries resulting in transfer. Head trauma accounted for 18.1% of skiing and 30.6% of snowboarding injuries resulting in transfer. Further, 20.0% of head trauma sustained by skiers resulted in transfer, as did 24.3% for snowboarders (data not shown in table). After head trauma, the most commonly transferred injuries were lower leg fractures (17.6%) and hip/femur fractures (16.3%) among skiers, and blunt chest trauma (10.4%) followed by blunt abdominal trauma (9.8%) for snowboarders.

Although falling to snow was the most common mechanism for injuries resulting in transfer (61.7% for skiers, 68.6% for snowboarders), collisions with natural objects accounted for 21.7% of transferred skiing injuries and 23.3% of transferred snowboarding injuries.

Additionally, 21.4% of snowboarding injuries resulting in transfer occurred in terrain parks compared to 9.6% of skiing injuries (data not shown in table).

Discussion

We observed several differences between skiers and snowboarders. Skiers most often injured their lower body and sustained sprains/strains while snowboarders injured their upper extremities and sustained fractures. A greater proportion of skiers were transferred compared to snowboarders. Age, sex, residence, use of rented equipment, ability level, slope difficulty and mechanism of injury also differed between sports. Given the observed differences, it will be important to deliver sport-specific injury prevention recommendations to most effectively decrease injury burden among winter sport participants.

At Winter Park Resort, over 60% of skiers and almost 70% of snowboarders were self-reported beginners or intermediates. Over 60% of both injured skiers and snowboarders were injured on easy (green) and intermediate (blue) slopes. Our results align with previous studies and a meta-analysis citing lower ability as a risk factor for injury.[16,92,93] A study comparing objective skill level to self-reported ability found that skiers and snowboarders overestimate their ability level, indicating an even greater proportion of injured participants may be beginners than self-reported.[94] Effectively educating novice skiers and snowboarders about ski resort safety and encouraging participants to ski or board within their limits remains a challenging yet important task for resorts.

Overall, we found a large proportion of skiers and snowboarders (~84%) were helmeted at the time of injury, which is higher than recent studies reporting between 52% and 80%.[18-20] Further, the proportion of helmet use at the time of injury increased significantly over the five study seasons for both sports from less than 80% to almost 90%. Although not yet at 100% and only reflective of injured participants, increases in the proportion of participants choosing to wear a helmet as demonstrated here and in multiple studies, likely reflects the successful promotion and adoption of an evidence-based injury prevention measure.[35,50,62,64,95]

Despite increased helmet use, head injuries remain a concern. Approximately 9% of injuries in both skiers and snowboarders were head trauma, which differs from previous findings of snowboarders experiencing proportionally more head injuries than skiers.[22,26,31,47,96] Head trauma was the most common injury resulting in transfer for both skiers (18.1%) and snowboarders (30.6%), and 20.0% of skiing-related head trauma and 24.3% of snowboarding-related head trauma were transferred. Out of all snowboarding injuries resulting in transfer, 21.4% occurred in terrain parks. Terrain parks are associated with increased injury severity and spine, neck, and head injuries, which may explain why a large proportion of injuries resulting in transfer among snowboarders involved head trauma.[15,97] Our results highlight the important role ski patrol and clinic physicians play in detecting the presence of severe head injuries and facilitating further evaluation and care when indicated. A computerized tomography (CT) scan and possibly overnight observation are necessary to evaluate a patient with suspected intracranial bleeding.[98] The clinic at the base of Winter Park Resort does not have CT scanning capabilities and closes overnight after ski patrol finishes sweeping (systematically closing the mountain while checking for injured people), necessitating transfer of patients with potentially significant head trauma.

We found a greater proportion of skiers (9.9%) were transferred compared to snowboarders (7.1%), which may be driven in part by sport-specific injury patterns. Skiers most frequently sustained lower extremity injuries. In general, upper extremity injuries (more frequently experienced by snowboarders) are more stable and less likely to require immediate transportation to a more advanced medical center.[11,28] In addition to head trauma, blunt trauma to the chest and abdomen were among the top 10 reasons for transfer in both skiers and snowboarders. Blunt traumatic injuries are of major concern due to their increased associated with fatalities. The Winter Park Resort clinic has plain radiography and ultrasound to evaluate for major bleeding. Ultrasound can guide initial management of blunt abdominal or chest trauma, but a CT scan is required to fully evaluate for intra-abdominal solid organ injuries such as splenic ruptures. One study of fatal skiing and snowboarding injuries in Colorado between 1980/81-2000/01 found that blunt traumatic injuries accounted for 34% of deaths, behind traumatic brain injuries (43%).[6] The same study showed that 65% of fatal injuries were the result of collisions with people and objects. Overall, we found that 12% of skiing and 9% of snowboarding injuries were due to collisions with objects (natural and man-made), but for injuries resulting in transfer, 22% among skiers and 23% among snowboarders were due to collisions with natural objects. Efforts focusing on preventing collisions would yield decreases in overall injuries and even larger decreases in more severe injuries.

We found the most common injury diagnoses were knee sprains among skiers and wrist fractures among snowboarders. Similar findings have been consistently observed across many studies over time.[11,37,39,58,91] Prior studies have demonstrated effectiveness of equipment-related injury prevention measures for knee and wrist injuries; for snowboarders, wearing wrist guards especially during the learning phase when falls are more likely, and for skiers, lowering binding setting so skis release more easily during a fall.[14,31-34] However, neither the prevalence of knee injuries in skiers nor wrist injuries in snowboarders has declined significantly since the 1980s, suggesting that recreational participants may not be aware of or be effectively implementing injury prevention measures.[26,62,99] Increasing uptake of evidence-based interventions could decrease the frequency of these commonly observed injuries.

Limitations

Our study had several strengths and limitations. This study included a large sample of injuries collected over five seasons at Winter Park Resort, a major Colorado ski resort. We may have underestimated the true number of injuries sustained as persons who sought medical care elsewhere, or not at all, were not included. However, the proximity of the clinic from which injury records were obtained relative to this resort increases the likelihood of capturing injuries requiring immediate clinical management; the nearest trauma center is located 20 miles from the resort, and the nearest Level I trauma center more the 60 miles from the resort. We only included one diagnosis per patient for analysis, possibly underestimating the prevalence of some injuries. However, by including the first listed diagnosis, the most clinically important injuries (in the clinic physicians' opinion) were evaluated. Information on ability, slope difficulty, and equipment ownership were only captured for patients presenting to ski patrol, and they may differ from patients only presenting to the clinic. Our study only included injured participants, so we could not make conclusive statements about injury risk. We also only included patients from one resort, which may not be reflective of the experience of other resorts. However, Winter Park Resort is one of the most visited resorts in the U.S and it is the closest destination resort to a major international airport in Colorado, indicating our study may include a diverse sample of participants.

Conclusions

In a population of injured skiers and snowboarders at Winter Park Resort, a majority of injured participants were beginners or intermediates. The most frequent injuries were knee ligament sprains among skiers and wrist fractures among snowboarders. While falls were the most common injury mechanism, collisions with objects were of concern, especially for injuries resulting in transfer. Head trauma was the most common injury resulting in transfer for both sports. Increased understanding of injury patterns among skiers and snowboarders may help with management of patients presenting for clinical care in the prehospital setting, as well as developing targeted injury preventive measures.

Tables and figures

Table 4.1 Comparison of demographics and other characteristics between skiers and snowboarders, Winter Park Resort, 2012/13-2016/17 seasons.

	Skiers n = 3,961	**Snowboarders n = 2,428**	**p-value**	**Cramer's V**
Variable[¥]				
Age (years)	Mean (SD)	Mean (SD)	**<0.001**	
	34.3 (19.3)	23.2 (10.5)		
Sex	**n (%)**	**n (%)**		
Male	2,127 (53.7)	1,754 (72.2)	**<0.001**	0.18
Female	1,834 (46.3)	674 (27.8)		
Total	3,961 (100.0)	2,428 (100.0)		
Residence	**n (%)**	**n (%)**		
Colorado	1,601 (40.4)	1,091 (45.0)	**<0.001**	0.04
Out of state	2,158 (54.5)	1,270 (52.2)		
Foreign	202 (5.1)	67 (2.8)		
Total	3,961 (100.0)	2,428 (100.0)		
Helmet	**n (%)**	**n (%)**		
Yes	3,017 (84.4)	1,916 (84.5)	0.93	<0.01
No	556 (15.6)	351 (15.5)		
Missing	*388*	*161*		
Total	3,573 (100.0)	2,267 (100.0)		
Initial presentation for care	**n (%)**	**n (%)**		
Clinic	500 (12.6)	305 (12.6)	0.94	<0.01
Ski patrol	3,461 (87.4)	2,123 (87.4)		
Total	3,961 (100.0)	2,428 (100.0)		
Equipment ownership*	**n (%)**	**n (%)**		
Rented/borrowed	1,608 (49.8)	874 (43.5)	**<0.001**	0.06
Owned	1,622 (50.2)	1,136 (56.5)		
Missing	*731*	*418*		
Total	3,230 (100.0)	2,010 (100.0)		
Ability level*	**n (%)**	**n (%)**		
Beginner	877 (25.5)	822 (38.9)		
Intermediate	1,300 (37.8)	649 (30.7)	**<0.001**	0.17
Advanced	695 (20.2)	458 (21.7)		
Expert	566 (16.5)	184 (8.7)		
Missing	*523*	*315*		
Total	3,438 (100.0)	2,113 (100.0)		

[¥]Missing values not included in totals, calculation of percentages, or in chi-square analysis comparing skiers and snowboarders. SD = standard deviation. Bold indicates statistical significance ($p<0.05$). *Equipment ownership and ability level were only obtained for the patients who presented to ski patrol first (3,461 skiers and 2,123 snowboarders). Out of those initially presenting to ski patrol, equipment ownership was missing for 231 skiers and 113 snowboarders; ability level was missing for 25 skiers and 12 snowboarders.

Table 4.2 Comparison of slope difficulty, injury mechanism, and disposition between skiers and snowboarders, Winter Park Resort, 2012/13-2016/17 seasons.

	Skiers n = 3,961	**Snowboarders** n = 2,428	**p-value**	**Cramer's V**
Variable[¥]	**n (%)**	**n (%)**		
Slope difficulty*				
Green, easiest	1,075 (31.7)	914 (43.4)		
Blue, intermediate	1,074 (31.7)	450 (21.3)		
Blue/black, advanced intermediate	363 (10.7)	101 (4.8)		
Black, most difficult	259 (7.6)	48 (2.3)		
Double black, expert	14 (0.4)	1 (<0.1)		
Trees	177 (5.2)	107 (5.1)	**<0.001**	0.016
Terrain park	205 (6.1)	339 (16.1)		
Lift/lift line-related	115 (3.4)	52 (2.5)		
Other[§]	104 (3.1)	96 (4.6)		
Missing	*575*	*320*		
Total	3,386 (100.0)	2,108 (100.0)		
Injury mechanism	**n (%)**	**n (%)**		
Fall to snow	2,855 (72.3)	2,056 (84.8)		
Collision with natural object	384 (9.7)	180 (7.4)		
Collision with another person	246 (6.2)	63 (2.6)		
Contact with own equipment	158 (4.0)	19 (0.8)		
Collision with man-made object	101 (2.5)	43 (1.8)		
Fall loading/unloading chair lift	90 (2.3)	37 (1.5)	**<0.001**	0.26
Non-contact	101 (2.5)	22 (0.9)		
Fall from chair lift from height	12 (0.3)	2 (0.1)		
Struck by moving chairlift	6 (0.2)	3 (0.1)		
Struck by moving vehicle (e.g., snowmobile)	1 (<0.1)	0 (0.0)		
Missing	*7*	*3*		
Total	3,954 (100.0)	2,425 (100.0)		
Disposition	**n (%)**	**n (%)**		
Transferred to another medical facility**	393 (9.9)	173 (7.1)	**<0.001**	0.05
Discharged home	3,568 (90.1)	2,255 (92.9)		
Total	3,961 (100.0)	2,428 (100.0)		

[¥]Missing values not included in calculation of percentages or in chi-square analysis comparing skiers and snowboarders. Bold indicates statistical significance (p<0.05). *Slope difficulty was obtained only for patients who presented to ski patrol first (3,459 skiers and 2,123 snowboarders). Out of those initially presenting to ski patrol, slope difficulty was missing for 75 skiers and 15 snowboarders. [§]Other includes areas not classified as slopes or do not have a rating (e.g., base area flats, flats near lunch areas, some catwalks, etc.) **Transferred to another facility includes those who were instructed to seek immediate further medical care via a personally owned vehicle, ambulance, air, or other forms of transportation.

Table 4.3 Top 10 most common specific injury diagnoses among skiers and snowboarders, Winter Park Resort, 2012/13-2016/17 seasons.

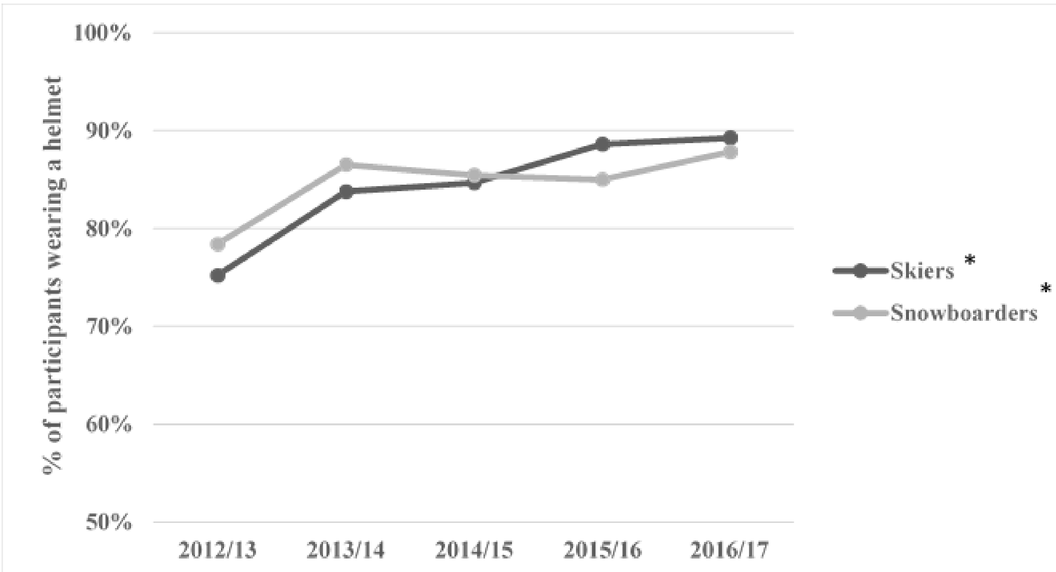
Skiers n = 3,961		**Snowboarders n = 2,428**	
Specific diagnosis*	**n (%)**	**Specific diagnosis***	**n (%)**
Knee sprain	823 (20.5)	Wrist fracture	623 (25.7)
Head trauma	354 (8.9)	Shoulder (acromioclavicular joint) separation	221 (9.1)
Clavicle fracture	178 (4.5)	Head trauma	218 (9.0)
Ankle fracture	166 (4.2)	Clavicle fracture	215 (8.9)
Lower leg fracture	154 (3.9)	Shoulder (glenohumeral joint) dislocation	101 (4.2)
Shoulder (acromioclavicular joint) separation	151 (3.8)	Wrist sprain	88 (3.6)
Shoulder (glenohumeral joint) dislocation	140 (3.5)	Knee sprain	82 (3.4)
Wrist fracture	130 (3.3)	Ankle sprain	53 (2.2)
Upper arm fracture	104 (2.6)	Rib fracture	43 (1.8)
Tibial plateau fracture	96 (2.4)	Upper arm fracture	38 (1.6)

* Knee sprains include all grades. Head trauma includes any trauma to the head excluding superficial injuries such as contusions/lacerations/abrasions. Ankle fractures include distal tibial/fibular fractures. Lower leg fractures include tibial/fibular mid-shaft fractures.

Table 4.4 Top 10 most common specific injury diagnoses resulting in transfer among skiers and snowboarders, Winter Park Resort, 2012/13-2016/17 seasons

Skiers n = 393		**Snowboarders n = 173**	
Specific diagnosis	**n (%)**	**Specific diagnosis**	**n (%)**
Head trauma	71 (18.1)	Head trauma	53 (30.6)
Lower leg fracture	69 (17.6)	Blunt chest trauma	18 (10.4)
Hip/femur fracture	65 (16.3)	Blunt abdominal trauma	17 (9.8)
Tibial plateau fracture	27 (6.9)	Hip/femur fracture	10 (5.8)
Blunt chest trauma	25 (6.4)	Lumbar spine fracture	8 (4.6)
Ankle fracture	17 (4.3)	Lower leg fracture	8 (4.6)
Blunt abdominal trauma	17 (4.3)	Ankle fracture	5 (2.9)
Pelvis fracture	16 (4.1)	Pelvis fracture	5 (2.9)
Lumbar spine fracture	13 (3.3)	Thoracic spine fracture	5 (2.9)
Thoracic spine fracture	8 (2.0)	Forearm fracture	5 (2.9)

*Head trauma includes any trauma to the head excluding superficial injuries such as contusions/lacerations/abrasions. Ankle fractures include distal tibial/fibular fractures. Lower leg fractures include tibial/fibular mid-shaft fractures.



*p<0.05 for increase in proportion of injured participants wearing helmets.

Figure 4.1 Proportion of helmet use among injured skiers and snowboarders over time, Winter Park Resort, 2012/13-2016/17 seasons.

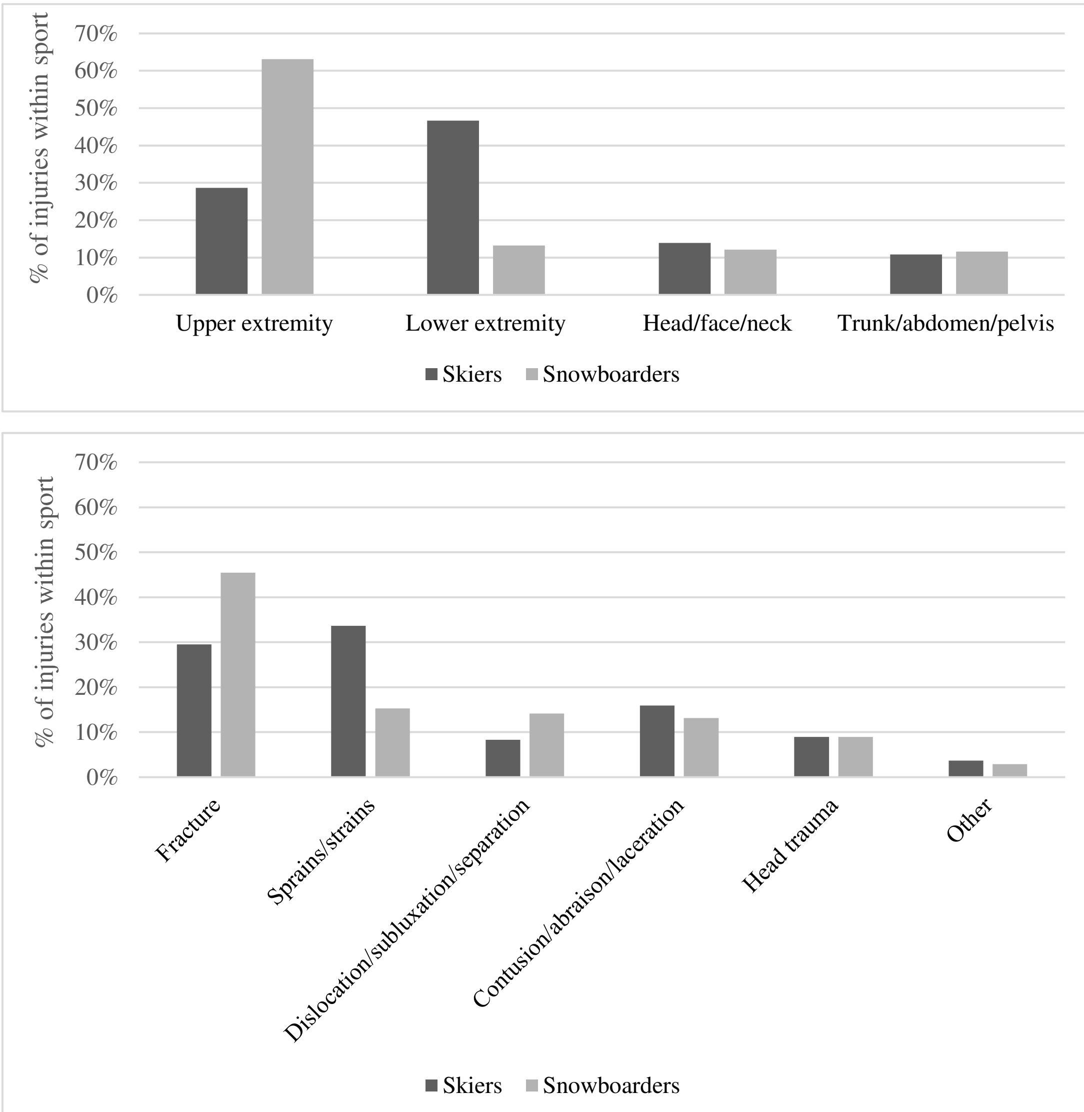


Figure 4.2 Most commonly injured body regions and diagnoses among skiers and snowboarders, Winter Park Resort, 2012/13-2016/17.

CHAPTER V

THE EFFECT OF ENVIRONMENTAL CONDITIONS ON INJURY RATES AT A COLORADO SKI RESORT

Abstract

Objective: To determine the effect of daily environmental conditions on skiing- and snowboarding-related injury rates. Methods: Injury information was collected from a mountainside clinic at a large Colorado ski resort for the 2012/13-2016/17 seasons. Daily environmental conditions including snowfall, snow base depth, temperature, open acres, and participant-visits were obtained from historical resort records. Snowpack and visibility information were obtained for the 2013/14-2014/15 seasons and included in a sub-analysis. Negative binomial regression was used to estimate injury rate ratios (IRR) and 95% confidence intervals (CI). Results: The overall injury rate among skiers and snowboarders was 1.37 per 1,000 participant-visits during 2012/13-2016/17. After adjustment for other environmental covariates, injury rates were 22% higher (IRR=1.22, 95%CI=1.14-1.29) on days with <1 inch compared to ≥1 inch of snowfall, and 14% higher on days with average temperature in the highest quartile (≥26.5°F) compared to the lowest (<13.0°F; IRR=1.14, 95%CI=1.03-1.26). Rates decreased by 8% for every 10-inch increase in snow base depth (IRR=0.92, 95%CI=0.88-0.95). In a sub-analysis of the 2013/14-2014/15 seasons including the same covariates plus snowpack and visibility, only snowpack remained significantly associated with injury rates. Rates were 71% higher on hardpack compared to powder days (IRR=1.71, 95%CI=1.18-2.49) and 36% higher on packed powder compared to powder days (IRR=1.36, 95%CI=1.12-1.64). Conclusions: Environmental conditions, particularly snowfall and snowpack, have a significant

impact on injury rates. Injury prevention efforts should consider environmental factors to decrease injury rates in skiers and snowboarders.

Introduction

Nearly 10 million people participate in skiing and snowboarding annually in the United States (U.S.) which accounted for almost 55 million visits to ski resorts during the 2016/17 season.[100,101] Consequently, each year up to 140,000 skiing and snowboarding-related injuries are treated in U.S. emergency departments (EDs).[11,26] Despite multiple studies on injury risk factors[11,26,31,37,42,47,48,65,84], there remains a need to decrease the substantial number of injuries that occur among skiers and snowboarders.

The potential effect of the environment on injury rates among skiers and snowboarders is an underexplored area of research.[9,12,18,67,69,71] Most research on skiing and snowboarding risk factors has instead focused on individual characteristics, yet behaviors such as wearing a helmet or voluntarily slowing down can be difficult to change and are only one part of the injury prevention paradigm.[102] Understanding of the role of environmental (extrinsic) factors, which all skiers and snowboarders must interact with, is a step forward in identifying new avenues for injury prevention at the skier and snowboarder population level.[21] Although weather itself is non-modifiable, increased knowledge of the relationship between environmental factors and injury rates may help better predict when and where injuries occur and should drive effective on-hill safety practices.

Two models of injury etiology emphasize the importance of the environment in affecting the transfer of injury-causing energy to a person.[19,21] One example specific to skiers and snowboarders is increased snowfall slowing speeds, thereby reducing severity or preventing injury altogether. Since skiers and snowboarders operate in extreme alpine environments, it is important to understand how conditions may affect injury risk. It is also important to understand if resort crowdedness, a significant part of the ski resort environment, affects injury rates. To our knowledge, no prior study has calculated and compared injury rates by daily environmental conditions.

In this study, we explored the association between differing environmental conditions and injury rates among recreational skiers and snowboarders using five seasons of data collected from a large Colorado ski resort. We hypothesized that injury rates would be higher on days with less snowfall, poorer visibility, more firm snow conditions, and on more crowded days. Information gleaned from this study will increase understanding of environmental characteristics and help clinicians, ski patrollers, skiers/snowboarders, and resort managers who are interested in improving safety by informing more effective injury prevention efforts.

Methods

Study design and setting

This retrospective cohort study included data collected from Winter Park Resort, a large Colorado ski resort during the 2012/13-2016/17 ski seasons. Winter Park Resort has 3,081 acres of terrain and a base elevation of 9,000ft. There is a community clinic/emergency care facility (Level V trauma center) located directly at the base of the ski area. There are no other emergency medical facilities located within 20 miles of the resort and the nearest Level I trauma center is 65 miles away in a major metropolitan area. Thus, the Winter Park Resort clinic is the most accessible for emergency medical treatment for injuries sustained at the resort and should capture the majority of moderate to serious skiing and snowboard related injuries that occur at the resort. The study was approved by the Colorado Multiple Institutions Review Board (#13-1730).

Data collection

Two researchers performed a retrospective chart review of records for all injured patients treated in the clinic during the 2012/13-2016/17 ski seasons. An injury was defined as one that resulted directly from skiing or snowboarding at Winter Park Resort, involved trauma to the musculoskeletal system or internal organs, and presented at the resort-side clinic. Patients could present to the clinic in multiple ways. Those who were injured on the hill and unable to ski or snowboard were taken down by ski patrol, triaged, and then transferred to the clinic if deemed necessary. Independently mobile injured persons could present to ski patrol first and be triaged similarly, or present directly to the clinic. Only injuries ultimately treated in the clinic which received a definitive diagnosis through physician evaluation were included.

Daily environmental measures recorded by Winter Park Resort were obtained from management and included open acreage, participant-visits (number of unique scanned tickets or passes), 24-hour snowfall (inches accumulated daily, measured at 5:30 AM), snow base depth (inches), and temperature (low and high temperatures, °F). For the 2013/14 and 2014/15 ski seasons only, snow condition (e.g., power, packed powder) and visibility (e.g., clear, partly cloudy) were additionally available. Snow conditions and visibility were determined by the resort personnel as the overriding weather conditions observed throughout the day.

Study measures

The primary outcome measure was rate of injury reported per 1,000 participant-visits. The number of injuries included in the study reflects the number of patients, not the number of separate injury diagnoses (e.g., a person who sustained a fracture and a ligament sprain is counted as one injury).

The main weather-related variables of interest included snowfall, temperature, base depth, snow conditions, and visibility. Other environmental variables included the proportion of the resort open on a given day (%) and measures of resort crowdedness including attendance (daily participant-visits) and participant-density (computed as the number of participants per open acre per day). Snowfall was categorized into <1 inch and ≥1 inch.[9] Temperature (average of high and low) was divided into quartiles.[18] Skier density was categorized into >11 and ≤11 skiers per acre (top 10% of days and bottom 90%, respectively). Attendance was categorized into >5,000 and ≤5,000 participant-visits (median). Snow conditions were classified by the resort as powder, powder/packed powder (mixture of powder and packed snow), packed powder, hardpack (firm snow surface), machine-made (blown early season to increase base depth), and spring conditions (variable due to nighttime freezing and subsequent daytime melting). Visibility was classified by the resort as clear, mostly clear, partly cloudy, mostly cloudy and cloudy. Season, month, and weekends/holidays compared to regular weekdays were evaluated as potential confounders.

Analysis

All analyses were performed in SAS V9.4 (Cary, NC). Prior to analysis, data were inspected for quality, normality, and missingness. The last week of the 2015/16 season was excluded for missing injury information and the last week of the 2016/17 season was excluded for missing attendance information. The main analysis was conducted on environmental conditions and injury rates from 2012/13-2016/17. A sub-analysis was conducted on data from 2013/14-2014/15 to determine if visibility and snowpack impacted findings.

Associations between injury rates and covariates were assessed using negative binomial regression yielding injury rate ratio estimates (IRR) with 95% confidence intervals (CI). Covariates univariately associated with injury rates ($p<0.20$) were entered into a multivariable model. Season, month, and weekends/holidays compared to regular weekdays were associated with injury rates and therefore included in the multivariable model to control for secular time trends and potential confounding. We ran separate models excluding days where <10% of terrain was open due to concerns of strong confounding by early season (higher-participant density, fewer participant-visits, and machine-made snow). After exclusion, no estimates changed >5%, therefore results including all days are presented. In the multivariable models, IRR whose 95%CI excluded 1.00 were considered statistically significant.

Results

Environmental and injury data

During the 2012/13-2016/17 seasons, daily environmental and injury data were available for 815 operating days. Researchers reviewed 7,523 clinic records for injuries occurring during the study period and excluded 1,128 unrelated to skiing or snowboarding resulting in a final sample of 6,395 injuries. These injuries occurred during 4,681,595 participant-visits for an overall injury rate of 1.37 per 1,000 participant-visits. The number of individuals presenting annually to the clinic ranged from a low of 1,208 to a high of 1,383 (**Figure 5.1**). Injury rates did not change significantly over the study period ($p=0.06$). Average environmental conditions by season are presented in **Table 5.1**. Seasonal total snowfall ranged from 238 to 351 inches, average daily snowfall from 1.5 to 2.1 inches, and average daily temperatures from 18.4 to 21.4°F.

Univariate associations

Table 5.2 presents injury counts, rates and univariate rate ratios associated with environmental factors. Injury rates were significantly higher on days with <1 inch of snowfall (IRR=1.32, 95%CI=1.24-1.42) compared to days with ≥1 inch. Rates increased across quartiles of increasing average temperature with the largest association on the warmest days compared to the coldest (IRR=1.34, 95%CI=1.22-1.47 for ≥ 26.5°F compared to <13°F). Snow base depth was not significantly associated with injury rates. Injury rates were lower on days with more participant-visits (IRR=0.86, 95%CI=0.81-0.93 for ≥5,000 compared to <5,000) and higher participant-density (IRR=0.78, 95%CI=0.67-0.91 for ≥11 compared to <11 people per acre). Rates increased by 4% for every additional 10% increase in open acreage (IRR=1.04, 95%CI=1.02-1.05). In the univariate sub-analysis of the 2013/14-2014/15 seasons, injury rates were higher on hardpack compared to powder days (IRR=1.87, 95%CI=1.28-2.75). However, injury rates were lower on cloudy compared to clear days (IRR=0.66, 95%CI=0.57-0.76). We also observed significant relationships for packed powder and spring conditions compared to powder, and for partly cloudy and mostly cloudy compared to clear (**Table 5.2**).

Multivariable model

Table 5.3 shows the rate ratios for each environmental condition adjusted for season, month, and weekends/holidays vs. weekdays. Snowfall, temperature, base depth, and the proportion of the resort that was open were all independently associated with injury rates in the multivariable model. Injury rates were 22% higher on days with <1 inch compared to days with ≥1 inch of snowfall (IRR=1.22, 95%CI=1.14-1.29). Rates decreased by 8% for every 10-inch increase in snow base depth (IRR=0.92, 95%CI=0.88-0.95). The relationship between temperature and rates remained significant but attenuated (IRR=1.14, 95%CI=1.03-1.26 for ≥ 26.5°F compared to <13°F; see **Table 5.3** for comparisons of other quartiles). In the sub-analysis of the 2013/14-2014/15 seasons, after additional adjustment for visibility and snowpack, only snowpack remained significantly associated with injury rates (**Table 5.4**). Compared to power days, injury rates were 71% higher on hard pack days (IRR=1.71, 95%CI=1.18-2.49) and 36% higher on packed powder days (IRR=1.36, 95%CI=1.12-1.64).

Discussion

Our study, the first of its kind to calculate and compare daily rates of injury across multiple environmental conditions, contributes new information to the body of literature on risk factors for skiers and snowboarders. In this study of injuries that occurred at a large ski resort over five seasons, we found that environmental conditions, specifically snow conditions, were strongly and independently associated with higher injury rates. After consideration of visibility and snowpack, only snowpack remained independently associated with injury rates such that rates increased by 22% on days with <1 inch of snowfall compared to days with ≥1 inch. Hardpack conditions were associated with a 71% increase in injury rates compared to powder days.

Overall injury rates

We observed an injury rate of 1.37 per 1,000 participant-visits, which is lower than previously reported injury rates. U.S. and international studies using ski patrol report forms as their primary data source have reported rates between 1.4 and 6.1 per 1,000 participant-visits.[11,13,29-34] The current study population only includes injuries treated in a resort-side medical clinic, excluding those solely managed by ski patrol. Ski patrol incident report forms capture more injuries than resort clinics.[37] However, resort clinics capture more injuries than hospitals which could explain why we observed higher rates than studies of injuries presenting to emergency departments or trauma centers.[16,38] Such evaluations of hospital-based data present reported rates between 0.06 and 0.7 per 1,000 participant-visits, but included only the most severe injuries or specific injuries types (e.g., spinal cord injury).[38,40,41]

Snowfall and injury rates

Adjusting for other environmental covariates, we found injury rates were 22% higher on days with <1 inch of snowfall. Our findings are consistent with the limited literature reporting objectively measured snowfall, which suggests that increased snowfall is a protective factor for injury.[9,65] Girardi *et al.* found that injuries were less severe on days with past 24-hour snowfall in South Tyrol, Italy between 2002-2005.[65] A study in Vail, CO in the 2011/12 season reported 66% of injuries occurred with ≤1 inch of snowfall and that ≤2 inches was associated with increased injury severity.[9] Snowfall is integral to resort operations, and we showed that it is also an important factor for decreasing injury rates. We also observed an 8% decrease in injury rates for every 10-inch increase in base depth. To our knowledge base depth has not previously been considered as an environmental factor. Although the magnitude of association is small, it was present after controlling for other factors that may affect base depth, such as temperature and month in season. Our findings suggest that ski patrol and resort management should consider the relationship between base depth and injury rates when making decisions related to opening/closing terrain.

Temperature and injury rates

Our study found higher injury rates on warmer days (top three quartiles) compared to the coldest (lowest quartile). Few studies of recreational skiers and snowboarders have evaluated objectively measured temperature as a risk factor for injury. In an Austrian study of non-contact falls during the 2008/09 season, Ruedl *et al.* reported a higher prevalence of knee injuries among females only in the lowest quartile of temperature compared to the highest (-11°C compared to 3°C).[18] Girardi *et al.* found no significant relationship between injury severity and temperature.[65] We hypothesized that colder temperatures would result in higher injury rates, as biomechanical and basic science studies have shown cooler temperatures may interfere with muscle performance and nerve conduction velocity.[75,103,104] Cooler snow temperatures may also increase grip on ski edges, increasing the likelihood of "catching an edge" which can lead to falling unexpectedly or forcing the knee into a valgus position, common with anterior cruciate ligament injuries.[59,105] However, according to our results ski patrol and clinics should expect higher injury rates on warmer days.

Participant density and injury rates

We did not find evidence for more crowded days increasing overall injury risk. In contrast to our hypothesis, injury rates were lower on days with higher participant density and greater attendance. This finding may reflect the influence of early season conditions, as neither factor was significant upon adjustment for other conditions and factors that affect crowdedness. One case series study of 73 snowboarders injured during the 1988/89-1989/90 seasons suggested that traffic (crowdedness) was not an important risk factor, as 59% of patients reported "light traffic" at the time of injury.[48] Since we could not calculate rates for specific locations which may experience increased traffic, further examination of the association between crowdedness and injury rates is warranted.

Sub-analysis for snowpack and visibility, 2013/14-2014/15

When we included visibility and snowpack conditions into the multivariable model for 2013/14-2014/15, only snowpack remained significantly associated with injury rates, with higher injury rates on days with increasingly harder snow compared to powder days. Our results are consistent with case-control studies citing “icy” or “grippy” snow as a risk factor for injury.[12,17,69,71] A 71% increase in injury rates on hardpack compared to powder days is an important finding as resorts have control over slope grooming. On days with hardpacked or packed powder snow, injury risk may be decreased by monitoring the state of the slopes closely, and implementing injury prevention measures such as grooming more often or placing additional signs to slow and safely direct participants down the hill.[17,67] Machine made snow did not increase injury risk in our study. However, other resorts receiving less annual snowfall may rely more heavily on machine made snow throughout a greater proportion of the season. Future studies should assess whether our findings are universally observed.

Univariately, we observed lower injury rates on cloudy days. After adjusting for other factors, visibility was not significantly associated with injury rates. Prior research on visibility has yielded equivocal findings. A meta-analysis based on three studies found that poor visibility increased the odds of injury for skiers and snowboarders (pooled OR=2.69, 95%CI=1.42-5.07).[67] Hasler *et al.* performed two case-control studies in Switzerland during 2007/08 and found a strong association between poor visibility and injury for snowboarders (OR=19.06, 95%CI=2.70-134.73)[12] but a non-significant association for skiers (OR=2.59, 95%CI=0.89-7.39).[71] Conversely, a case-control study of Dutch skiers during the 1984/85 season found a protective effect (OR=0.4, 95%CI=0.3-0.7) for poor visibility compared to good.[17] These prior case-control studies used subjective measures of visibility reported by injured individuals, whereas the current study used daily visibility statistics provided by the resort as part of their weather reports to compare injury incidence under differing conditions. Visibility at higher altitudes can be extremely transient, thus reported visibility may not be an accurate reflection of visibility conditions at the time of injury, resulting in non-differential misclassification and therefore an increased likelihood of committing a type 2 error.

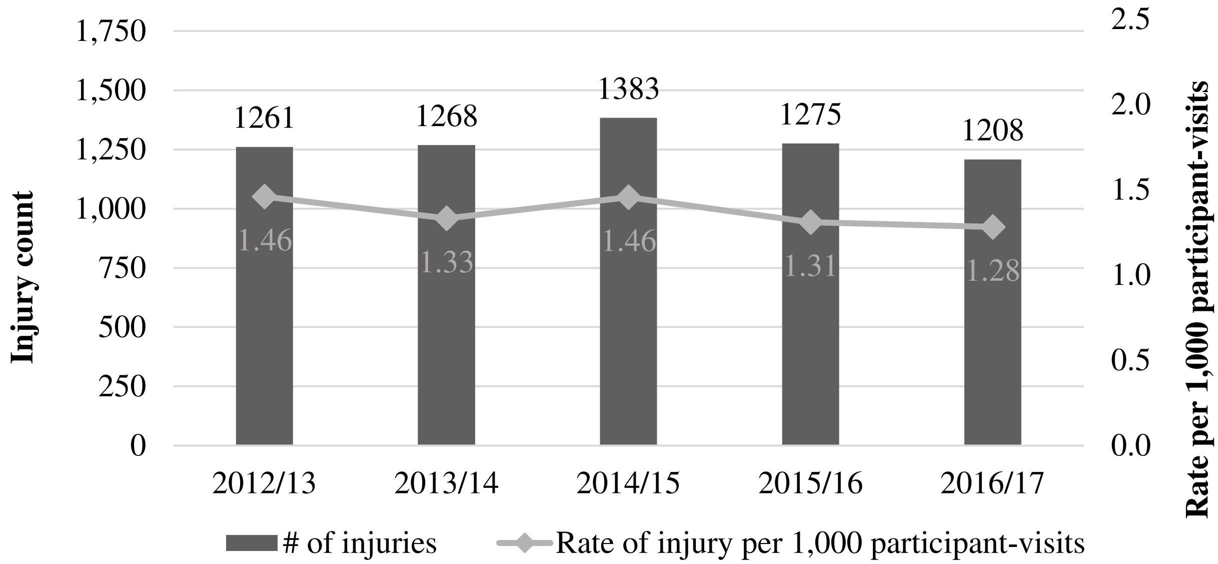
Limitations

Our study has several important strengths and weaknesses that should be considered within the context of the study design. The current study reports clinically diagnosed injury rates based on daily participant-visits across five seasons at one of the largest resorts in Colorado with objectively measured environmental conditions. To our knowledge this is the first study to report injury rates by environmental condition using daily participant-visits as opposed to aggregate seasonal participant-visits. An additional strength includes multivariable analyses to evaluate multiple environmental risk factors simultaneously. However, we were unable to incorporate denominator data on individual experience level, frequency of participation, gender, or activity (skier versus snowboarder) which may be an important predictors of injury risk. The use of participant-visits as the denominator for rate calculations assumes the same level of exposure for each person who accessed the resort regardless of how many runs they completed. Injured persons who sought medical care elsewhere, or not at all, were not included. A prior study estimated up to 27% of injured participants do not seek medical care which would result in an underestimation of rates.[11] However, the proximity of the clinic relative to the resort increases the likelihood of capturing the majority of injuries requiring immediate clinical management such as fractures or severe injuries resulting in transport. Weather conditions can be unpredictable and variable, and given the strong relationship demonstrated in the current study, future research should be conducted incorporating study designs (e.g., case-crossover) to account for transient exposures.

Conclusion

Models of injury etiology state that injuries in general are inextricably linked to the environment that they occur in.[19,21] Considering strategies to modulate the impact of environmental conditions or individual behavior in response to environmental conditions could reduce the potential for injury among skiers and snowboarders. Our results provide strong evidence for including environmental factors when conducting studies of risk factors, providing clinical advice to patients on risk factors, and developing injury prevention programs.

Tables and figures



p = 0.06 for time trend

Figure 5.1 Injury counts and rates per 1,000 participant-visits among skiers and snowboarders over time, Winter Park Resort, 2012/13 through 2016/17 seasons.

Table 5.1 Resort characteristics and average environmental conditions, Winter Park Resort, 2012/13 through 2016/17 seasons.

	Seasonal total # of participant-visits	Seasonal total snowfall (inches)	Daily snowfall (inches)	Daily temperature (^{o}F)
	Total	Total	Mean (SD, Range)	Mean (SD)
2012/13	863,816	260	1.6 (2.4, 0.0-12.0)	19.0 (10.3)
2013/14	952,399	351	2.1 (3.0, 0.0-14.0)	18.4 (9.3)
2014/15	949,687	238	1.5 (2.6, 0.0-12.0)	21.4 (9.6)
2015/16	973,409	326	1.9 (3.0, 0.0-13.5)	19.6 (10.2)
2016/17	942,284	311	2.0 (2.8, 0.0-14.0)	20.9 (11.4)

Table 5.2 Counts, proportions, rates, and univariate rate ratios of injury among skiers and snowboarders by environmental factor, Winter Park Resort, 2012/13 through 2016/17 seasons.

Environmental characteristic	Injuries n (%)	Participant -visits (n)	Rate per 1,000 participant-visits	Crude IRR (95% CI)[a]
Total	6,395 (100.0)	4,681,595	1.37	N/A
Daily snowfall				
< 1 inch	3,900 (61.0)	2,543,644	1.53	**1.32 (1.24-1.42)**
≥ 1 inch	2,495 (39.0)	2,137,951	1.17	REF
Temperature (°F)				
< 13	1,494 (23.3)	1,267,796	1.18	REF
13 - < 20.5	1,793 (28.0)	1,385,424	1.29	**1.11 (1.01-1.22)**
20.5 - < 26.5	1,570 (24.6)	1,070,712	1.47	**1.24 (1.13-1.37)**
≥ 26.5	1,538 (24.1)	957,663	1.61	**1.34 (1.22-1.47)**
Snow base (continuous, inches)[b]	N/A	N/A	N/A	1.02 (1.00-1.04)
Attendance				
< 5,000 participant-visits	1,914 (29.9)	1,235,187	1.55	REF
≥ 5,000 participant-visits	4,481 (70.1)	3,446,408	1.30	**0.86 (0.81-0.93)**
Proportion of resort open (continuous, %)[c]	N/A	N/A	N/A	**1.04 (1.02-1.05)**
Participant density				
< 11 persons per acre	6,137 (95.9)	4,450,813	1.38	REF
≥ 11 persons per acre	258 (4.1)	230,782	1.12	**0.78 (0.67-0.91)**
Visibility[d]				
Clear	837 (31.8)	480,509	1.74	REF
Mostly clear	400 (15.2)	264,444	1.51	0.86 (0.72-1.04)
Partly cloudy	565 (21.5)	416,636	1.36	**0.79 (0.67-0.92)**
Mostly Cloudy	89 (3.4)	80,906	1.10	**0.61 (0.45-0.81)**
Cloudy	740 (28.1)	649,100	1.14	**0.66 (0.57-0.76)**
Snowpack conditions[d]				
Powder	259 (9.8)	259,548	1.00	REF
Powder/packed powder	403 (15.3)	347,322	1.16	1.16 (0.94-1.45)
Packed powder	1,522 (57.8)	1,016,202	1.50	**1.56 (1.29-1.87)**
Hardpack	67 (2.5)	43,751	1.53	**1.87 (1.28-2.75)**
Machine made	19 (0.7)	21,268	0.89	0.93 (0.55-1.55)
Spring	361 (13.7)	203,504	1.77	**1.69 (1.35-2.11)**

a. Injury rate ratios (IRR) modeled using negative binomial regression, CI = confidence interval, bold = significant at alpha level of 0.05, REF = referent category.
b. IRR reflects change in injury rate per 10-inch increase in base depth.
c. IRR reflects change in injury rate per 10% increase in open acreage.
d. Visibility and snow conditions were obtained for 2013/14 and 2014/15 seasons only (327 total days included, 1 day during 2014/15 was missing visibility and snow condition information). All other variables were obtained for every season (815 days).

Table 5.3 Adjusted[a] rate ratios between environmental factors and injury rates among skiers and snowboarders, Winter Park Resort, 2012/13 through 2016/17 seasons.

Environmental characteristic	**Adjusted IRR (95% CI)[b]**
Daily snowfall	
< 1 inch	**1.22 (1.14-1.29)**
≥ 1 inch	REF
Temperature (°F)	
< 13	REF
13 - < 20.5	**1.10 (1.01-1.19)**
20.5 - < 26.5	**1.15 (1.05-1.25)**
≥ 26.5	**1.14 (1.03-1.26)**
Snow base (continuous, inches)[c]	**0.92 (0.88-0.95)**
Attendance	
< 5,000 participant-visits	REF
≥ 5,000 participant-visits	0.94 (0.87-1.02)
Proportion of resort open (continuous, %)[d]	**1.06 (1.03-1.10)**
Participant density	
< 11 persons per acre	REF
≥ 11 persons per acre	0.88 (0.68-1.13)

a. Each variable adjusted for month, season, holiday/weekend vs. weekday, and all other variables listed in the table.
b. Injury rate ratios (IRR) modeled using negative binomial regression, CI = confidence interval, bold = significant at alpha level of 0.05, REF = referent category.
c. Rate ratio reflects change in injury rate per 10-inch increase in base depth.
d. Rate ratio reflects change in injury rate per 10% increase in open acreage.

Table 5.4 Adjusted[a] associations for sub-analysis including visibility and snowpack information, Winter Park Resort, 2013/14 through 2014/15 seasons.

Environmental characteristic	Adjusted IRR (95% CI)[b]
Daily snowfall	
< 1 inch	1.03 (0.89-1.20)
≥ 1 inch	REF
Temperature (°F)	
< 13	REF
13 - < 20.5	1.05 (0.91-1.22)
20.5 - < 26.5	1.04 (0.90-1.22)
≥ 26.5	1.09 (0.91-1.33)
Snow base (continuous, inches)[c]	0.93 (0.86-1.00)
Attendance	
< 5,000 participant-visits	REF
≥ 5,000 participant-visits	1.05 (0.91-1.20)
Proportion of resort open (continuous, %)[d]	1.06 (1.00-1.12)
Participant density	
< 11 persons per acre	REF
≥ 11 persons per acre	0.85 (0.47-1.51)
Visibility[e,f]	
Clear	REF
Mostly clear	0.93 (0.79-1.09)
Partly cloudy	0.88 (0.77-1.02)
Mostly Cloudy	0.78 (0.59-1.02)
Cloudy	0.83 (0.72-0.97)
Snowpack conditions[f]	
Powder	REF
Powder/packed powder	1.10 (0.91-1.33)
Packed powder	**1.36 (1.12-1.64)**
Hardpack	**1.71 (1.18-2.49)**
Machine made	0.84 (0.48-1.47)
Spring	1.06 (0.79-1.41)

a. Adjusted for season, month, weekend/holiday vs weekday, and all other variables listed in the table.
b. Injury rate ratios (IRR) modeled using negative binomial regression, CI = confidence interval, bold = significant at alpha level of 0.05, REF = referent category.
c. Rate ratio reflects change in injury rate per 10 inch increase in base depth.
d. Rate ratio reflects change in injury rate per 10% increase in open acreage.
e. Type III analyses were not significant for the overall effect of visibility (p=0.14).
f. Visibility and snow conditions were obtained for 2013/14 and 2014/15 seasons only (327 total days included, 1 day during 2014/15 was missing visibility and snow condition information). All other variables were obtained for every season (815 days).

CHAPTER VII

EVALUATION OF INTRINSIC AND EXTRINSIC FACTORS ASSOCIATED WITH INJURY PATTERNS AMOGN RECREATIONAL SKIERS AND SNOWBOARDERS AT A MAJOR UNITED STATES SKI RESORT

Abstract

Introduction: Skiing and snowboarding, enjoyed by millions worldwide, carry risk for significant injury. Research evaluating the effect intrinsic and extrinsic factors have on injury patterns can inform injury prevention efforts at resorts. Methods: Data were collected at Winter Park Resort for the 2012/13-2016/17 seasons and included demographics/characteristics (age, sex, ability), injury event information (run difficulty, injury mechanism), and injury information (body site, diagnosis, disposition). Multivariable logistic regression (multinomial or binary) evaluated the independent effects of intrinsic and extrinsic factors for outcomes including: mechanism of injury, injured body region, injury diagnosis, and disposition. Adjusted odds ratios (OR) and 95% confidence intervals (CI) were computed; results were considered significant if the 95%CI excluded 1.00. Results: Data included 6,389 injured skiers and snowboarders. Males were more likely than females to sustain contact-related injuries vs. fall-related injuries (OR=1.66, 95%CI=1.39-1.99) and injuries resulting in transfer (OR=1.43, 95%CI=1.14-1.81). Individuals aged 65+ years (vs. 15-24) had over three times the odds of sustaining fractures vs. head trauma (OR=3.30, 95%CI=2.32-4.68). Snowboarders had lower odds of sustaining collision-related vs. fall-related injuries (OR=0.49, 95%CI=0.36-0.68), and higher odds of upper extremity vs. head/face/neck injury (OR=2.45, 95%CI=2.02-2.96) compared to skiers. Less snowfall (<1 inch vs. ≥1 inch) increased the odds of collision-related vs. fall-related injury (OR=1.30, 95%CI=1.01-1.68). Conclusion: Sex and age were independent influential intrinsic

factors and sport and snowfall influential independent extrinsic factors associated with injury. Results can inform future evidence-based targeted injury prevention efforts.

Introduction

Over 10 million people participate in alpine skiing and snowboarding annually, amounting to more than 50 million United States (U.S.) ski resort visits in the 2016/17 season.[1] An estimated 140,000 skiing- and snowboarding-related injuries are treated annually in U.S. emergency departments (ED).[2] Serious yet common injuries such as traumatic brain injury or knee ligament ruptures may result in substantial healthcare costs and lead to lifelong disability.[3-5]

Despite numerous epidemiologic studies of winter sport injuries, the lack of multivariable analyses incorporating detailed covariate information, such as environmental factors, is a major limitation in the field.[13,39,48,91,106] According to a classic conceptual model of sports injury etiology, injuries result from the complex interplay of intrinsic factors (e.g., demographics) and extrinsic factors (e.g., equipment, weather), initiated by an inciting event (e.g., mechanism of injury).[19] While prior studies have shown the most effective approaches for injury prevention are multifactorial[21], there has been little research on the extent to which intrinsic and extrinsic factors contribute and interact to influence skiing- and snowboarding-related injury patterns in the U.S. Research to quantify this relationship is warranted to drive improved targeted prevention efforts.

The purpose of this study was to identify influential independent factors related to injury patterns among recreational skiers and snowboarders at Winter Park Resort, one of the largest resorts in the U.S. This study aimed to advance the current understanding of ski- and snowboard-related injuries by simultaneously assessing a combination of risk factors, using data collected from a mountainside medical clinic. We hypothesized that extrinsic factors would remain significantly associated with injury patterns after adjustment for known intrinsic risk factors (age, sex, ability). Specifically, we anticipated that snowfall, difficulty of slope, and resort crowdedness would demonstrate strong associations with injury patterns. Study results will contribute to the evidence-base that ultimately informs decision-making surrounding skier and snowboarder safety. Ultimately, the long-term goals of this research were to reduce the frequency and severity of skiing- and snowboarding-related injuries.

Methods

Setting and population

Data were collected on a cohort of skiers and snowboarders injured at Winter Park Resort during the 2012/13-2016/17 ski seasons. Following injury on the ski slope, individuals were evaluated initially by either ski patrol or in a combined level V trauma center and community clinic at the base of the resort. Individuals evaluated initially by ski patrol were triaged and transferred to the clinic for further treatment and diagnostics, if deemed necessary. For this study, only individuals treated in the clinic who received a definitive physician diagnosis were included. Individuals with environmental injuries (e.g., sunburns, frostbite) or illnesses (e.g., upper respiratory infection, altitude sickness), and those injured during other activities (e.g., tubing, snowmobiling) were excluded. All protocols and procedures were approved by the Colorado Multiple Institutions Review Board (#13-1730).

Data collection

Data were obtained from the medical clinic, ski patrol, and resort management. Injury information (e.g., body site, diagnosis) was collected from clinic records via medical chart review. For the 2012/13-2015/16 seasons, two research assistants reviewed and extracted information from hand-written clinic notes scanned into a semi-electronic health record. In 2016/17, Winter Park Resort implemented an electronic health record system, making data available through electronic queries. The first listed diagnosis in the record (the most clinically important in the physician's opinion) was used for analyses unless the individual sustained head trauma (excluding superficial injuries such as abrasions) or a fracture, in which case the head trauma or fracture were also included. If the individual sustained head trauma and a fracture, head trauma was included for analyses and the fracture marked as a secondary injury. If injury diagnoses were unclear, a physician practicing at the medical clinic was consulted for categorization.

Age, sex, residence, helmet use, injury mechanism, and disposition were also obtained from clinic records. Self-reported ski or snowboard ability level, slope difficulty on which the injury occurred, and use of rental, borrowed, or owned ski equipment were collected from ski patrol records. Ski patrol information was only available for individuals who were initially evaluated by ski patrol and not those who presented directly to the clinic. Resort management provided daily resort conditions including low and high temperatures (°F), past 24-hour snowfall (inches), snow base depth (inches), attendance (participant-visits), and open acreage.

Study measures

The primary outcome measures were mechanism of injury, injured body region, diagnosis, and disposition. Mechanism of injury was categorized into falls, collisions (two or more participants colliding), contact with objects (man-made or natural), and non-contact (no contact with ground, objects or people). Body region injured was categorized into head/face/neck, upper extremity, trunk, and lower extremity. Injury diagnoses were grouped as fractures, head trauma, sprains/strains, superficial injuries (contusions, abrasions, lacerations), internal injuries (injuries to organs), dislocations/separations (including subluxations), and other. Disposition was dichotomized into transferred or discharged home. Transferred patients included those sent to another medical facility via ambulance or helicopter, and those instructed by the clinic physician to seek further care but who chose to transfer themselves.

Intrinsic covariates included age, sex, ability level, and residence. Extrinsic covariates included sport, helmet use, equipment ownership, difficulty of run, snowfall, temperature, time of day base depth, open acreage, and attendance. Participant density, an additional extrinsic factor measuring resort crowdedness was computed as the number of participants per open acre.

Missing data and multiple imputation

Ski ability (13.1% missing), difficulty of slope (14.0% missing), and equipment ownership (18.6% missing) were not collected from individuals who bypassed ski patrol. In the overall cohort, helmet use was unknown in 8.6% of the individuals, resulting in complete data for 75.6% of the entire study population. Multiple imputation was implemented to account for the missing data using the fully conditional specification method.[80] Analyses using the imputed data were conducted and compared against the original dataset with pairwise deletion. Since the findings were similar, results from the findings using multiple imputation are presented.

Analysis

Logistic regression models were performed to evaluate the association between intrinsic/extrinsic factors and disposition (transferred vs. discharged home). Multinomial logistic regression was used to model the association between intrinsic/extrinsic factors and the nominal outcomes of mechanism of injury, injured body region, and diagnosis. Falls were chosen as the reference group for mechanism of injury as the largest category. The head/face/neck for body region and head trauma for diagnosis were chosen as referent groups, as head injuries are a major concern across diverse groups of stakeholders.[22,64,78]

Covariates whose univariate associations with aforementioned outcomes yielded a p-value <0.20 were included in a preliminary multivariable model. In addition to the intrinsic and extrinsic variables described previously, mechanism of injury was evaluated as a covariate for all other outcomes; body region and diagnosis were evaluated as covariates for disposition.[19] Non-contact injuries and diagnoses classified as "other" were excluded from injury diagnosis analyses due to complete separation of the data (expected cell sizes of 0). If there was evidence of multicollinearity between independent variables (Spearman or Pearson correlations >0.80), the variable most strongly associated with the outcome was included. Variables not included in the preliminary model were introduced and retained if any other parameter estimate changed >15.0%, regardless of significance. Odds ratios (OR) with 95% confidence intervals (CI) were computed and results were considered statistically significant if the 95% CI did not contain 1.00. All analyses were performed in SAS V9.4 (Cary, NC).

Results

Overall sample

Researchers reviewed 7,523 clinic records and excluded 1,128 for being unrelated to skiing or snowboarding, with 6 additional cases removed for having neither skiing nor snowboarding marked as the primary activity (specific sport was not specified, but box was checked for skiing/snowboarding-related). This yielded a final sample size of 6,389 skiers and snowboarders evaluated in the clinic during the 2012/13-2016/17 ski seasons. **Tables 6.1 and 6.2** show distributions of each covariate and their bivariate association with the outcome measures. All intrinsic factors were significantly associated with each outcome, as were the extrinsic factors of sport, equipment ownership, and difficulty of run. Other extrinsic factors exhibited more variable associations (**Table 6.2**).

Mechanism of injury

Figure 6.1 displays the adjusted multinomial logistic regression results for mechanism of injury as the outcome of interest and falls as the reference group. Snowboarders had nearly 50% lower odds of sustaining a collision-related injury vs a fall compared to skiers (OR=0.49, 95%CI=0.36-0.68) and males had a 29% lower risk compared to females (OR=0.71, 95%CI=0.56-0.92). Compared to the young adult age group of 15-24 year-olds, the youngest (<15 years) and oldest (65+) age groups were more likely to sustaining a collision-related injury as compared to a fall-related injury (OR=1.49, 95%CI=1.02-2.18; OR=1.83, 95%CI=1.24-2.71, respectively). The odds of being injured in a collision compared to a fall also increased with increasing ability levels; the largest difference found in experts compared to beginners (OR=3.15, 95%CI=1.86-5.33). Injuries sustained in terrain parks (OR=0.15, 95%CI=0.06-0.38), blue/black (intermediate/advanced) runs (OR=0.30, 95%CI=0.16-0.55), and black (advanced) runs (OR=0.25, 95%CI=0.12-0.55) when compared to blue (intermediate) runs, all had lower odds of being collision-related compared to fall-related. On days with <1 inch of snow compared to ≥1 inch, the odds of sustaining an injury in a collision compared to a fall increased by 30% (OR=1.30, 95%CI=1.01-1.68).

When comparing injuries sustained by contact with objects to fall-related injuries, snowboarders had lower odds of injury compared to skiers (OR=0.38, 95%CI=0.32-0.47) whereas males had higher odds of injury compared to females (OR=1.66, 95%CI=1.39-1.99). The odds of being injured due to contact with an object declined with increasing age when compared to fall-related injuries; the largest effect size was observed in the 65+ age group compared to 15-24 year-olds (OR=0.36, 95%CI=0.27-0.50). Advanced and expert skiers/snowboarders had increased odds of being injured due to contact with objects compared beginners (OR=1.46, 95%CI=1.09-1.97 and OR=1.56, 95%CI=1.11-2.18, respectively). Rental equipment use was associated with decreased odds of injury from contact with objects compared to fall-related injuries (OR=0.77, OR=0.62-0.97). Injuries that occurred on black (advanced) runs (OR=1.71, 95%CI=1.24-2.36) and on tree runs (OR=16.65, 95%CI=12.03-23.06) were positively associated with injuries due to contact with objects as compared to blue (intermediate) runs; the opposite association was found for terrain parks (OR=0.62, 95%CI=0.44-0.88).

In comparison to fall-related injuries, snowboarders were less likely to sustain non-contact injuries than skiers (OR=0.38, 95%CI=0.22-0.64). Individuals age 35-49 had an increased odds of non-contact injuries compared to fall-related, when compared to 15-24 year-olds (OR=1.89, 95%CI=1.05-3.32). Additionally, injuries sustained on black (advanced) runs were more likely to be non-contact compared to blue (intermediate) runs (OR=3.14, 95%CI=1.57-6.29).

Body region

Figure 6.2 displays the adjusted multinomial logistic regression results for body region as the outcome of interest with head/face/neck as the reference group. Compared to skiers, snowboarders had higher odds of injuring their trunk (OR=1.44, 95%CI=1.13-1.84) and upper extremities (OR=2.45, 95%CI=2.02-2.96) compared to their head/face/neck, but lower odds of sustaining a lower extremity injury (OR=0.36, 95%CI=0.29-0.44). Compared to females, males had reduced odds of sustaining a lower extremity injury than a head/face/neck injury (OR=0.67, 95%CI=0.56-0.80). Older individuals, ages 35+ compared to those age 15-24 years, had increased odds of sustaining injuries to all other body regions compared to the head/face/neck (see **Figure 6.2**). Compared to blue (intermediate) runs, injuries sustained on black (advanced) runs, blue/black (intermediate/advanced) runs, and on tree runs had a higher odds of resulting in lower extremity injuries compared to head/face/neck injuries (OR=1.92, 95%CI=1.25-2.96, OR=1.59, 95%CI=1.10-2.28, and OR=1.92, 95%CI=1.27-2.91, respectively). Compared to fall-related injuries, injuries sustained during collisions with other people had reduced odds of affecting the lower or upper extremity as compared the head/face/neck (OR=0.33, 95%CI=0.23-0.46 and OR=0.36, 95%CI=0.25-0.50, respectively).

Diagnosis

Figure 6.3 displays the adjusted multinomial logistic regression results for diagnosis as the outcome of interest with head trauma as the reference group (F**igure 6.3**). Compared to head trauma, we found snowboarders had higher odds of sustaining dislocations/separations (OR=1.60, 95%CI=1.21-2.11) and fractures (OR=2.08, 95%CI=1.65-2.63), but lower odds of sustaining sprain/strains (OR=0.55, 95%CI=0.43-0.71), compared to skiers. Compared to females, males had higher odds of sustaining dislocations/separations (OR=3.06, 95%CI=2.31-4.05), but lower odds of sustaining sprains/strains (OR=0.70, 95%CI=0.57-0.88) compared to head trauma. Compared to 15-24 year-olds, older age was associated with an increased odds of sustaining any other injury type when compared to head trauma. The magnitude and significance level of the association varied by diagnosis type (**Figure 6.3**). For example, individuals age 65+ had over three times the odds of sustaining fractures compared to head trauma (OR=3.30, 95%CI=2.32-4.68). Injuries sustained on black (advanced) runs compared to blue (intermediate) runs had higher odds of sprains/strains (OR=1.83, 95%CI=1.07-3.14) and superficial injuries (OR=2.49, 95%CI=1.41-4.40) compared to head trauma. Additional differences in difficulty of run and diagnosis subtype were observed but varied in magnitude and direction (see **Figure 6.3**).

Disposition

Figure 6.4 displays the adjusted logistic regression results for disposition as the outcome of interest, with discharged home as the reference group (**Figure 6.4**). The odds of being transferred to another healthcare facility were higher among males compared to females (OR=1.43, 95%CI=1.14-1.81) and lower among children <15 years compared to their 15-24 year-old counterparts (OR=0.55, 95%CI=0.39-0.78). Non-residents had reduced odds of being transferred compared to Colorado residents (OR=0.70, 95%CI=0.55-0.89). Compared to fall-related injuries, individuals injured by contact with an object had increased odds of being transferred compared to discharged home (OR=1.85, 95%CI=1.37-2.49). When compared to head/face/neck injuries, all other body regions had lower odds of being transferred to another healthcare facility compared to being discharged home (see **Figure 6.4**). Fractures and internal injuries had higher odds of being transferred compared to head trauma (OR=5.50, 95%CI=3.09-9.82 and OR=17.71, 95%CI=7.94-39.50, respectively). Sport, ability level, equipment ownership, difficulty of run, temperature, and snowfall were not significantly associated with disposition.

Discussion

This is the first U.S. study to identify influential independent intrinsic and extrinsic factors associated with multiple injury outcomes among recreational skiers and snowboarders. The intrinsic factors of sex and age were strongly associated with all outcomes assessed (mechanism of injury, injured body region, injury diagnosis, and disposition). Mechanism of injury was also an important factor for injured body region, diagnosis, and disposition. Sport, difficulty of slope, and snowfall measures were influential extrinsic factors, while other environmental variables (skier density, temperature) were found not to be associated with injury patterns as hypothesized.

Compared to fall-related injuries, contact with objects increased the odds of being transferred to another healthcare facility by 85%, independent of injured body region or injury diagnosis. This finding indicates that similar injuries were more severe when participants collided with objects. A similar, non-significant trend was observed for collisions with other individuals. These results support previous findings that collisions with objects and other participants result in more serious injuries than falls.[6,9] Although most injuries at resorts result from falls[13,26], preventing collisions and contact with objects would not only lower overall injury frequency but would also have an arguably larger impact decreasing injury severity. Prevention efforts are also relevant to U.S. ski resorts, as collision-related injuries can result in litigation, despite being considered "inherent dangers of skiing" under many state statues.[107-109] All U.S. resorts have adopted versions of the "Responsibility Code", a set of regulations developed by the National Ski Areas Association (NSAA) designed to educate participants about slope safety and individual responsibility for avoiding collisions. Although widely promoted, the NSAA regulations' effectiveness have not been evaluated, and prior work shows the presence of regulations may not directly translate into skier or snowboarder knowledge. A 2009 cross-sectional survey of 1,400 Austrian skiers found that 25% were unaware safety rules existed, and only 52% provided correct answers about contents of the regulations.[107] Ski patrols currently implement collision prevention measures such as placing signs instructing slower speeds at intersections and padding man-made objects, though it is not feasible to pad every obstacle in a ski resort. Additional prevention efforts may warrant identifying areas of increased collision risk and then effectively eliminating/reducing the risk by directing skier and snowboarder traffic at these recognized dangerous intersections.[48,73]

This study identified male sex and younger age as subgroups with increased odds of injury during collisions with objects compared to falls. This aligns with prior research showing males and younger participants are more likely to engage in risk-taking behavior, including speeding, which may impair one's ability to slow down and avoid obstacles.[110-112] In contrast, we found the 65+ age group had higher odds of injury during collisions with other participants compared to falls than the 15-24 year-olds. However, older participants may not be at higher risk for collision; rather, collisions involving older individuals may more frequently result in injury due to age-related physiological factors such as decreased bone density, reaction times, and flexibility.[113-115] The odds of injury during a collision compared to a fall increased with increasing ability level, though the association is likely driven by a decrease in the probability of falling among more skilled participants.[91]

Although collisions with other individuals and objects are concerning, most skiing and snowboarding injuries are caused by falls.[28,38,116] This study demonstrated that snowboarders had lower odds of experiencing an injury by any other mechanism compared to falling, independent of ability level as compared to skiers. Snowboarders also had increased odds of sustaining upper extremity injuries and fractures, compared to head injuries and head trauma. Upper extremity injuries are well-established as the most common injuries among snowboarders.[11,46,91] Wrist fractures, the most common specific injury, frequently result from falling on an outstretched hand which can be prevented by wearing wrist guards.[58,90,117-119] A 2002 randomized controlled trial testing the effect of wrist guards among Austrian snowboarders found that failing to wear wrist guards significantly increased the risk of a moderate to severe wrist injury (risk ratio=2.78, 95% CI=1.05–7.35).[120] A more recent systematic review found that that wearing wrist guards decreases the risk of a wrist injury in snowboarders by up to 87%.[118,119] Despite a clear protective effect, wrist guard use among snowboarders is not nearly as widespread as helmet use: the prevalence of wrist guard use is between 1% and 7% while helmet use is above 80%.[13,35,64,118,119] Ensuring wrist guards are distributed as a part of the standard rental practices, as with helmets, may result in an increase in their usage.[121] Similarly, some resorts mandate helmet use during lessons; a strategy that if implemented for wrist guards, may prevent wrist injuries that occur during lessons and set precedence for future use.

The present study also found skiers and females were more likely to sustain sprains/strains and lower extremity injuries compared to snowboarders and males, respectively. These results have been consistently observed in the literature, highlighting a need for more effective prevention strategies.[11,31,39,46-48,58] Binding release failure has been implicated in lower leg fractures and anterior cruciate ligament ruptures.[122] Recreational skiers must be vigilant in maintaining their equipment and ensuring their bindings are set to release appropriately. Rental shops are required to adjust binding settings for individuals according to height, weight, and ability level prior to each use. While rental equipment is subjected to heavy use, it may be maintained more frequently by professionals than personal equipment, though prior studies found that use of rental equipment increases the odds of injury among children and first-day skiers or snowboarders.[67,123] In the current study, participants who owned their equipment had a 23% reduced odds of being injured in a collision with an object compared to a fall-related injury, and a 20% reduced odds of being transferred to another healthcare facility, although this was not statistically significant. It is unclear such results provide evidence that rental equipment influences overall injury risk, or if the use of rental gear is reflective of other participant characteristics influencing risk such as experience or other behavioral factors not measured in this study.

This study found few environmental factors associated with injury risk, possibly due to environmental conditions being aggregated daily and not specific to the time of injury. Weather can be extremely transient and can vary by location on the mountain and time of day. Prior case-control and cohort studies have shown that temperature, snowfall, visibility and snow conditions influence injury patterns.[12,62,65,71] The current study found the odds of being injured in collisions with other individuals as compared to falls were greater on days with <1 inch of snowfall. This finding may be due to individuals being unable to slow down and control their speed to avoid hitting other individuals on icy days with low snowfall. Increased signage or patrol presence monitoring speed on icy days may be necessary to decrease collisions between individuals on low snowfall days.

Limitations

These findings must be interpreted in accordance with the study limitations. First, the true number of injuries may have been underestimated, as injured participants who sought medical care elsewhere, or not at all, were not included. Though the proximity of the medical clinic relative to the resort increased the likelihood of capturing injuries in need of clinical management. Second, only data on injured participants was collected and analyzed; thus, injury risk relative to an uninjured comparison group could not be calculated. Third, multinomial logistic regression assumes exclusivity of the outcome categories. Only one diagnosis per individual was included, but some individuals sustained multiple injuries in one single event. Multinomial regression also requires clear explanations of results relative to reference groups and careful interpretation. Fourth, using disposition as a proxy for injury severity may result in misclassification. Individuals with an injury who were transferred may not have had a severe injury, but may instead have required advanced imaging (e.g. CT scan) not available at the medical clinic for appropriate diagnosis or need for observation overnight (clinic closes after the sweep in the evening) for conditions such as head trauma. Fifth, there are many unmeasured factors that might influence injury patterns (e.g., alcohol consumption). Finally, these results represent an injured population from a single resort, though the study included a large sample of injuries collected over five seasons from one of the largest ski resorts in the U.S.

Conclusion

This study identified important intrinsic and extrinsic factors associated with skiing and snowboarding injuries at a major U.S. ski resort. Future development of sex- and age-specific interventions may more effectively decrease injury incidence, as these intrinsic factors were found to be strongly associated with injury pattern and severity. Additional targeted prevention strategies aimed at reducing collisions with other people and objects would also decrease injury frequency and severity. Future studies assessing the impact of injury prevention efforts on the diverse sets of intrinsic and extrinsic factors identified discussed in this study are warranted.

Table 6.1 Distribution of intrinsic factors and associations with injury outcomes, Winter Park Resort, 2012/13-2016/17 seasons.

		Mechanism of injury				Injured Body Region			
Intrinsic factor*	**Total sample**	**Fall**	**Contact with object**	**Non-contact**	**Collision**	**Head/face/neck**	**Upper extremity**	**Trunk**	**Lower extremity**
Sex, n (%)		**p<0.001**				**p<0.001**			
Male	3881 (60.7)	3007 (59.5)	647 (72.3)	76 (61.8)	146 (47.3)	538 (63.7)	1805 (67.8)	480 (67.4)	1057 (48.8)
Female	2508 (39.3)	2045 (40.5)	248 (27.7)	47 (38.2)	163 (52.8)	306 (36.3)	859 (32.2)	232 (32.6)	1109 (51.2)
Age (years), n (%)		**p<0.001**				**p<0.001**			
<15	1269 (19.9)	990 (19.6)	204 (22.8)	8 (6.5)	66 (21.4)	226 (26.8)	568 (21.3)	110 (15.5)	363 (16.8)
15-24	1949 (30.5)	1554 (30.8)	305 (34.1)	28 (22.8)	58 (18.8)	312 (37.0)	925 (34.7)	217 (30.5)	495 (22.9)
25-34	941 (14.7)	757 (15.0)	135 (15.1)	19 (15.5)	30 (9.7)	95 (11.3)	426 (16.0)	105 (14.8)	315 (14.5)
35-49	717 (11.2)	569 (11.3)	88 (9.8)	24 (19.5)	35 (11.3)	57 (6.8)	247 (9.3)	77 (10.8)	335 (15.5)
50-64	758 (11.9)	598 (11.8)	94 (10.5)	24 (19.5)	42 (13.6)	59 (7.0)	256 (9.6)	80 (11.2)	363 (16.8)
65+	755 (11.8)	584 (11.6)	69 (7.7)	20 (16.3)	78 (25.2)	95 (11.3)	242 (9.1)	123 (17.3)	295 (13.6)
Residence, n (%)		**p=0.02**				**p<0.001**			
Colorado	2692 (42.1)	2028 (40.1)	458 (51.2)	51 (41.5)	150 (48.5)	395 (46.8)	1103 (41.4)	332 (46.6)	861 (39.8)
Out-of-state or foreign	3697 (57.9)	3024 (59.9)	437 (48.8)	72 (58.5)	159 (51.5)	449 (53.2)	1561 (58.6)	380 (53.4)	1305 (60.3)
Ability, n (%)¥		**p<0.001**				**p<0.001**			
Beginner	1699 (30.6)	1481 (33.7)	146 (18.7)	23 (24.0)	47 (17.4)	202 (27.1)	797 (34.0)	142 (23.6)	556 (29.9)
Intermediate	1949 (35.1)	1564 (35.6)	237 (30.4)	26 (27.1)	119 (44.1)	260 (34.9)	819 (35.0)	181 (30.1)	689 (37.0)
Advanced	1153 (20.8)	850 (19.3)	216 (27.7)	24 (25.0)	63 (23.3)	165 (22.2)	462 (19.7)	159 (26.5)	367 (19.7)
Expert	750 (13.5)	505 (11.5)	180 (23.1)	23 (24.0)	41 (15.2)	118 (15.8)	264 (11.3)	119 (19.8)	248 (13.3)

	Injury diagnosis							Disposition	
Intrinsic factor	**Fracture**	**Head trauma**	**Strain /sprain**	**Superficial injury**	**Dislocation /separation**	**Internal injury**	**Other**	**Transferred**	**Discharged home**
Sex, n (%)				**p<0.001**				**p<0.001**	
Male	1430 (62.9)	352 (61.4)	829 (46.8)	628 (66.2)	551 (82.0)	57 (79.2)	34 (44.7)	185 (32.7)	2323 (39.9)
Female	844 (37.1)	221 (38.6)	944 (53.2)	321 (33.8)	121 (18.0)	15 (20.8)	42 (55.3)	381 (67.3)	3500 (60.1)
Age (years), n (%)				**p<0.001**				**p<0.001**	
<15	564 (24.8)	155 (27.1)	244 (13.8)	236 (24.9)	33 (4.9)	11 (15.3)	26 (34.2)	80 (14.1)	1189 (20.4)
15-24	68 (27.6)	230 (40.1)	461 (26.0)	339 (35.7)	241 (35.9)	30 (41.7)	20 (26.3)	154 (27.2)	1795 (30.8)
25-34	307 (13.5)	65 (11.3)	258 (14.6)	118 (12.4)	171 (25.5)	13 (18.1)	9 (11.8)	92 (16.3)	849 (14.6)
35-49	229 (10.1)	32 (5.6)	288 (16.2)	82 (8.6)	74 (11.0)	8 (11.1)	4 (5.3)	61 (10.8)	656 (11.3)
50-64	236 (10.4)	28 (4.9)	310 (17.5)	94 (9.9)	81 (12.1)	4 (5.6)	5 (6.6)	65 (11.5)	693 (11.9)
65+	310 (13.6)	63 (11.0)	212 (12)	80 (8.4)	72 (10.7)	6 (8.3)	12 (15.8)	114 (20.1)	641 (11.0)
Residence, n (%)				**p<0.001**				**p<0.001**	
Colorado	981 (43.1)	261 (45.6)	649 (36.6)	419 (44.2)	303 (45.1)	39 (54.2)	40 (52.6)	304 (53.7)	2388 (41.0)
Out-of-state or foreign	1293 (56.9)	312 (54.5)	1124 (63.4)	530 (55.9)	369 (54.9)	33 (45.8)	36 (47.4)	262 (46.3)	3435 (59.0)
Ability, n (%)				**p<0.001**				**p<0.001**	
Beginner	672 (32.7)	148 (28.7)	498 (33.9)	213 (26.9)	132 (22.2)	12 (19.4)	24 (36.9)	118 (22.1)	1581 (31.5)
Intermediate	744 (36.2)	187 (36.3)	501 (34.1)	251 (31.7)	227 (38.1)	17 (27.4)	22 (33.9)	188 (35.2)	1761 (35.1)
Advanced	412 (20.1)	110 (21.4)	272 (18.5)	184 (23.3)	150 (25.2)	16 (25.8)	9 (13.9)	136 (25.5)	1017 (20.3)
Expert	226 (11.0)	70 (13.6)	197 (13.4)	143 (18.1)	87 (14.6)	17 (27.4)	10 (15.4)	92 (17.2)	658 (13.1)

*n and % reflect raw, unimputed data. Column percentages add to 100% for each intrinsic factor by outcome level. ¥837 cases (13.1%) of ability, 10 cases (0.2%) for mechanism of injury, and 3 cases (0.05%) for body region were missing. P-values reflect results from bivariate logistic or multinomial logistic regression using imputed data. Bold indicates statistical significance at p<0.05.

Table 6.2a. Distribution of extrinsic factors and associations with outcomes, Winter Park Resort, 2012/13-2016/17 seasons.

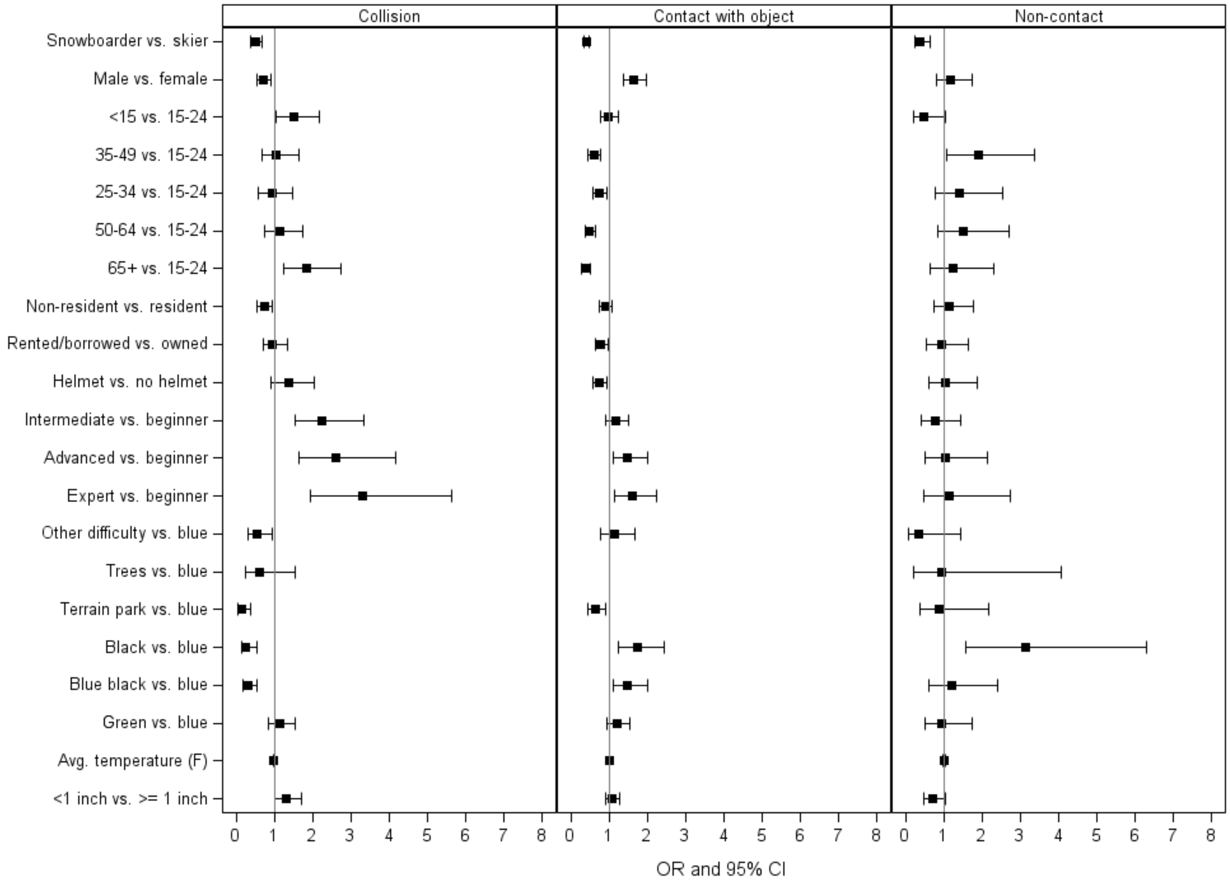
		Mechanism of injury				**Injured Body Region**			
Extrinsic factor*	**Total sample**	**Fall**	**Contact with object**	**Non-contact**	**Collision**	**Head/face/neck**	**Upper extremity**	**Trunk**	**Lower extremity**
Activity, n (%)		**p<0.001**				**p<0.001**			
Skier	3691 (62.0)	2957 (58.5)	650 (72.6)	101 (82.1)	246 (79.6)	550 (65.2)	1133 (42.5)	430 (60.4)	1846 (85.2)
Snowboarder	2428 (38.0)	2095 (41.5)	245 (27.4)	22 (17.9)	63 (20.4)	294 (34.8)	1531 (57.5)	282 (39.6)	320 (14.8)
Helmet use, n (%)¥		p=0.18				p=0.31			
Yes	4933 (84.5)	3898 (84.1)	690 (84.8)	85 (85.0)	252 (89.1)	676 (84.6)	2102 (85.4)	544 (84.0)	1609 (83.4)
No	907 (15.5)	736 (15.9)	124 (15.2)	15 (15.0)	31 (11.0)	123 (15.4)	359 (14.6)	104 (16.1)	321 (16.6)
Equipment, n (%)¥		**p<0.001**				**p<0.001**			
Owned	2482 (47.4)	2085 (50.3)	467 (62.9)	57 (59.4)	146 (57.7)	383 (54.2)	1182 (53.1)	338 (59.0)	852 (49.2)
Rented/borrowed	2758 (52.6)	2057 (49.7)	276 (37.2)	39 (40.6)	107 (42.3)	324 (45.8)	1043 (46.9)	235 (41.0)	880 (50.8)
Difficulty, n (%)¥		**p<0.001**				**p<0.001**			
Green (beginner)	2000 (35.7)	1670 (37.6)	192 (24.4)	29 (29.6)	108 (39.9)	238 (31.7)	939 (39.7)	183 (30.1)	640 (34.2)
Blue (intermediate)	1596 (28.5)	1284 (28.9)	166 (21.1)	28 (28.6)	117 (43.2)	220 (29.3)	669 (28.3)	159 (26.1)	548 (29.3)
Blue/black (intermediate/advanced)	463 (8.3)	357 (8)	82 (10.4)	11 (11.2)	13 (4.8)	56 (7.5)	172 (7.3)	39 (6.4)	196 (10.5)
Black (advanced)	333 (5.9)	229 (5.2)	76 (9.6)	19 (19.4)	8 (3.0)	40 (5.3)	94 (4.0)	40 (6.6)	158 (8.4)
Terrain park	545 (9.7)	483 (10.9)	50 (6.4)	7 (7.1)	5 (1.9)	84 (11.2)	287 (12.1)	85 (14.0)	89 (4.8)
Lift	150 (2.7)	141 (3.2)	9 (1.1)	0 (0.0)	0 (0.0)	14 (1.9)	42 (1.8)	22 (3.6)	72 (3.8)
Trees	232 (4.1)	184 (4.2)	28 (3.6)	2 (2.0)	15 (5.5)	48 (6.4)	98 (4.1)	25 (4.1)	59 (3.2)
Other	283 (5.1)	91 (2.1)	185 (23.5)	2 (2.0)	5 (1.9)	52 (6.9)	64 (2.7)	56 (9.2)	111 (5.9)
		p=0.05				**p=0.01**			
Temperature (F), mean (SD)	19.5 (9.5)	19.6 (9.6)	19.1 (9.4)	18.4 (9.6)	18.5 (15.4)	19.4 (9.6)	19.9 (9.5)	19.3 (9.5)	19.0 (9.5)
Snowfall, n (%)		**p=0.01**				**p=0.002**			
<1 inch	3898 (61.0)	3112 (61.6)	522 (58.3)	61 (49.6)	198 (64.1)	532 (63.0)	1677 (63.0)	436 (61.2)	1252 (57.8)
≥1 inch	2491 (39.0)	1940 (38.4)	373 (41.7)	62 (50.4)	111 (35.9)	312 (37.0)	987 (37.1)	276 (38.8)	914 (42.2)
Time of day, n (%)¥		p=0.28				p=0.35			
Morning	2659 (41.7)	2075 (41.2)	389 (43.6)	57 (46.3)	137 (44.3)	631 (42.9)	1084 (40.8)	315 (44.2)	898 (41.6)
Afternoon	3714 (58.3)	2964 (58.8)	503 (56.4)	66 (53.7)	172 (55.7)	480 (57.1)	1572 (59.2)	397 (55.8)	1263 (58.4)
		p=0.60				**p=0.02**			
Base depth (inches), mean (SD)	54.0 (16.0)	54.2 (16.2)	53.7 (15.6)	52.7 (15.4)	54.4 (15.4)	55.0 (15.5)	53.4 (16.4)	54.0 (15.4)	54.7 (16.0)
Attendance, n (%)		**p=0.02**				p=0.18			
>7000 participants	3296 (51.6)	2577 (51.0)	495 (55.3)	53 (43.1)	168 (54.4)	436 (51.7)	1347 (50.6)	355 (49.9)	1157 (53.4)
≤7000 participants	3093 (48.4)	2475 (49.0)	400 (44.7)	70 (56.9)	141 (45.6)	408 (48.3)	1317 (49.4)	357 (50.1)	1009 (46.6)
		p=0.31				**p=0.04**			
Acres open (%), mean (SD)	80.6 (24.7)	80.7 (24.8)	80.0 (24.8)	79.1 (26.0)	82.5 (23.7)	82.6 (22.3)	80.0 (26.3)	80.5 (24.9)	80.7 (23.7)
Participant density, n (%)		p=0.90				p=0.17			
>7 participants/acre	721 (11.3)	561 (11.1)	104 (11.6)	15 (12.2)	38 (12.3)	80 (9.5)	324 (12.2)	77 (10.8)	240 (11.1)
≤7 participants/acre	5668 (88.7)	4491 (88.9)	791 (88.4)	108 (87.8)	271 (87.7)	764 (90.5)	2340 (87.8)	635 (89.2)	1926 (88.9)

*n (%) and mean (SD) reflect raw, unimputed data. Column percentages add to 100% for each extrinsic factor by outcome level.
549 cases (8.6%) for helmet use, 1149 cases (18.0%) for equipment, 805 cases (12.6%) for difficulty, 16 cases (0.2%) for time of day, 10 cases (0.2%) for mechanism of injury, and 3 cases (0.05%) for body region were missing. P-values reflect results from bivariate logistic or multinomial logistic regression using imputed data. Bold indicates statistical significance at p<0.05.

Table 6.2b. Distribution of extrinsic factors and associations with outcomes. Winter Park Resort. 2012/13-2016/17 seasons.

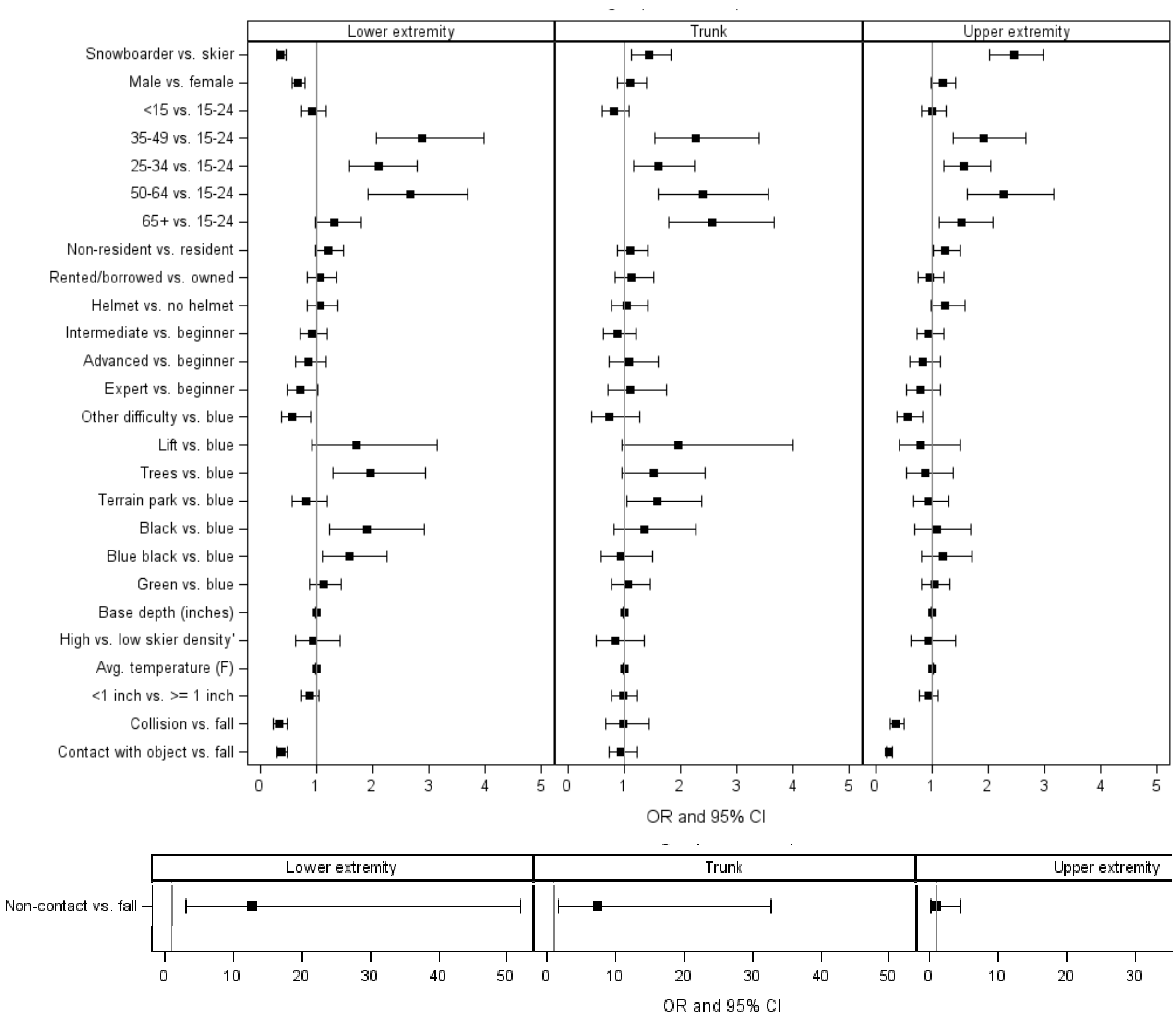
	Injury diagnosis							Disposition	
Extrinsic factor	**Fracture**	**Head trauma**	**Strain /sprain**	**Superficial injury**	**Dislocation /separation**	**Internal injury**	**Other**	**Transferred**	**Discharged home**
Activity, n (%)				**p<0.001**				**<0.001**	
Skier	1170 (51.5)	355 (62.0)	1387 (78.2)	630 (66.4)	328 (48.8)	36 (50.0)	55 (72.4)	393 (69.4)	3568 (61.3)
Snowboarder	1104 (48.6)	218 (38.1)	386 (21.8)	319 (33.6)	344 (51.2)	36 (50.0)	21 (27.6)	173 (30.6)	2255 (38.7)
Helmet use, n (%)				**p=0.04**				p=0.60	
Yes	1808 (85.0)	473 (86.5)	1304 (83.0)	721 (85.8)	510 (82.8)	50 (75.8)	67 (90.5)	446 (83.7)	4487 (84.6)
No	318 (15.0)	74 (13.5)	267 (17.0)	119 (14.2)	106 (17.2)	16 (24.2)	7 (9.5)	87 (16.3)	820 (15.5)
Equipment, n (%)				**p <0.001**				**p<0.001**	
Rented/borrowed	1014 (52.3)	259 (52.6)	635 (46.4)	422 (56.6)	363 (63.9)	37 (62.7)	28 (41.2)	326 (63.4)	2432 (51.5)
Owned	924 (47.7)	233 (47.4)	735 (53.7)	323 (43.4)	205 (36.1)	22 (37.3)	40 (58.8)	188 (36.6)	2294 (48.5)
Difficulty, n (%)[¥]				**p <0.001**				**p<0.001**	
Green	780 (37.8)	169 (32.6)	552 (37.3)	272 (33.9)	186 (30.9)	19 (30.7)	22 (32.4)	143 (26.6)	1857 (36.7)
Blue	581 (28.1)	153 (29.5)	442 (29.8)	177 (22.0)	204 (33.8)	17 (27.4)	22 (32.4)	169 (31.4)	1427 (28.2)
Blue/black	170 (8.2)	31 (6.0)	129 (8.7)	65 (8.1)	58 (9.6)	4 (6.5)	6 (8.8)	44 (8.2)	419 (8.3)
Black	93 (4.5)	21 (4.1)	108 (7.3)	71 (8.8)	30 (5.0)	5 (8.1)	5 (7.4)	34 (6.3)	299 (5.9)
Terrain park	228 (11.0)	66 (12.7)	81 (5.5)	79 (9.8)	82 (13.6)	9 (14.5)	0 (0.0)	63 (11.7)	482 (9.5)
Lift	49 (2.4)	12 (2.3)	57 (3.9)	22 (2.7)	5 (0.8)	1 (1.6)	4 (5.9)	17 (3.2)	133 (2.6)
Trees	75 (3.6)	41 (7.9)	59 (4.0)	38 (4.7)	15 (2.5)	1 (1.6)	3 (4.4)	16 (3.0)	216 (4.3)
Other	90 (4.4)	25 (4.8)	54 (3.6)	79 (9.8)	23 (3.8)	6 (9.7)	6 (8.8)	52 (9.7)	231 (4.6)
				p=0.07				p=0.63	
Temperature (F), mean (SD)	19.8 (9.4)	19.8 (9.7)	19.0 (9.7)	19.4 (9.7)	19.4 (9.4)	17.5 (9.5)	20.2 (11.0)	19.7 (9.9)	19.5 (9.5)
Snowfall, n (%)				p=0.26				p=0.55	
<1 inch	1413 (62.1)	368 (64.2)	1058 (59.7)	578 (60.9)	391 (58.2)	42 (58.3)	48 (63.2)	352 (62.2)	3546 (60.9)
≥1 inch	861 (37.9)	205 (35.8)	715 (40.3)	371 (39.1)	281 (41.8)	30 (41.7)	28 (36.8)	214 (37.8)	2277 (39.1)
Time of day, n (%)				p=0.30				p=0.07	
Morning	904 (39.9)	237 (41.4)	776 (43.8)	405 (42.8)	278 (41.6)	29 (40.3)	30 (39.5)	256 (45.3)	2403 (41.4)
Afternoon	1364 (60.1)	335 (58.6)	994 (56.2)	541 (57.2)	391 (58.4)	43 (59.7)	46 (60.5)	309 (54.7)	3405 (58.6)
				p=0.26				p=0.27	
Base depth (inches), mean (SD)	54.2 (16.5)	55.4 (15.2)	54.4 (16.3)	53.6 (15.3)	53.1 (15.5)	52.0 (14.7)	55.0 (12.8)	54.9 (15.7)	54.9 (16.2)
Attendance, n (%)				p=0.10				p=0.93	
>7000 participants	1197 (52.6)	292 (51.0)	900 (50.8)	503 (53.0)	317 (47.2)	43 (59.7)	44 (57.9)	291 (51.4)	3005 (51.6)
≤7000 participants	1077 (47.4)	281 (49.0)	873 (49.2)	446 (47.0)	355 (52.8)	29 (40.3)	32 (42.1)	275 (48.6)	2818 (48.4)
				p=0.11				p=0.33	
Acres open (%), mean (SD)	80.1 (25.7)	83.7 (24.4)	80.4 (24.4)	80.5 (24.7)	80.0 (25.4)	80.9 (26.2)	80.6 (22.4)	81.5 (24.8)	80.4 (24.9)
Participant density, n (%)				p=0.33				p=0.22	
>7 participants/acre	272 (12.0)	53 (9.3)	206 (11.6)	100 (10.5)	68 (10.1)	11 (15.3)	11 (14.5)	55 (9.7)	666 (11.4)
≤7 participants/acre	2002 (88.0)	520 (90.7)	1567 (88.4)	849 (89.5)	604 (89.9)	61 (84.7)	65 (85.5)	511 (90.3)	5157 (88.6)

*n (%) and mean (SD) reflect raw, unimputed data. Column percentages add to 100% for each factor by level of outcomes.
549 cases (8.6%) for helmet use, 1149 cases (18.0%) for equipment, 805 cases (12.6%) for difficulty, 16 cases (0.2%) for time of day, 10 cases (0.2%) for mechanism of injury, and 3 cases (0.05%) for body region were missing.
P-values reflect results from bivariate logistic or multinomial logistic regression using imputed data. Bold indicates statistical significance at p<0.05.



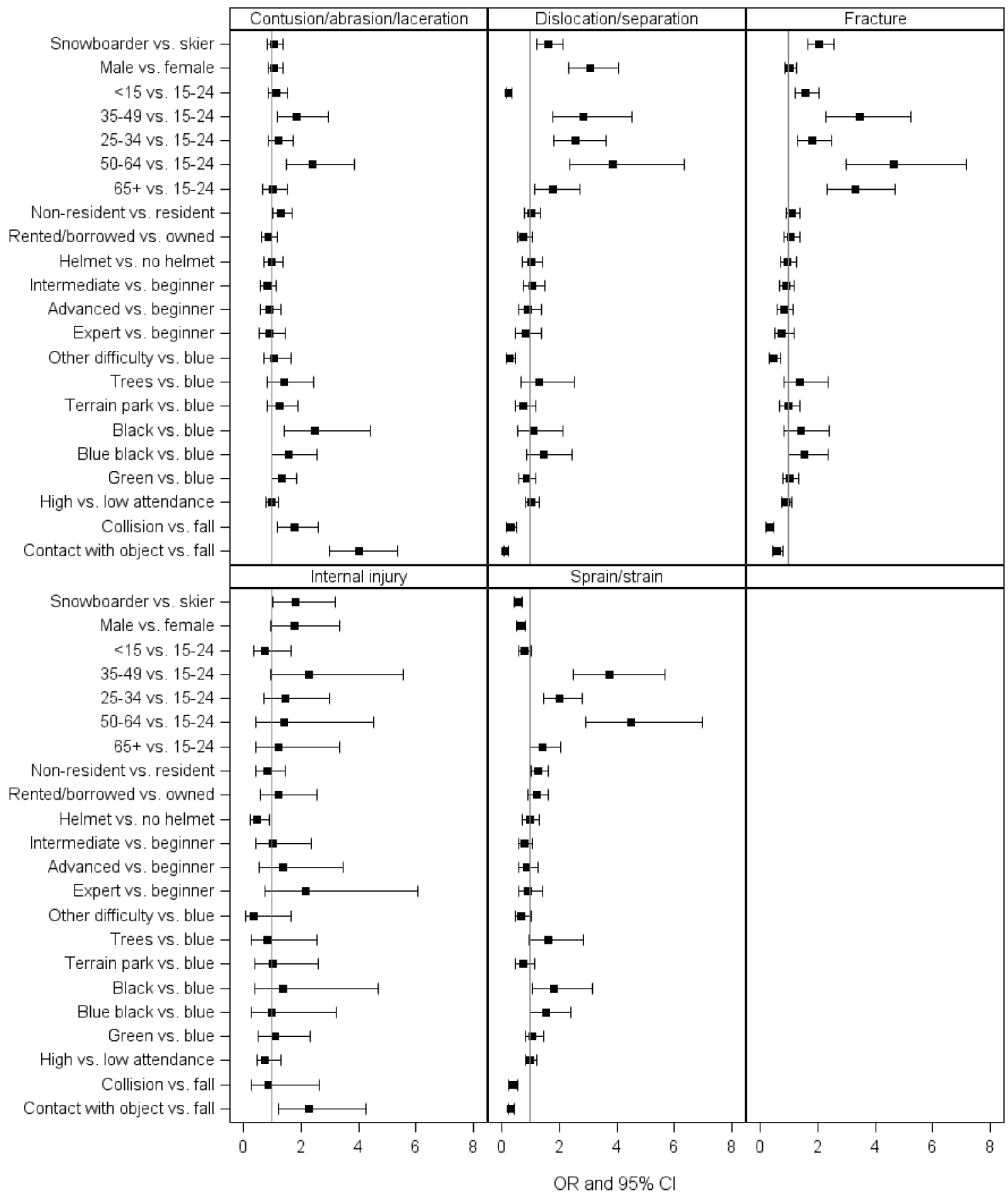
*OR = odds ratio, CI = confidence interval. Odds ratios represent associations between each risk factor and mechanism of injury, adjusted for all other factors in the figure.

Figure 6.1 Adjusted odds ratios and 95% confidence intervals for outcome of mechanism of injury, Winter Park Resort, 2012/13-2016/17 seasons*.



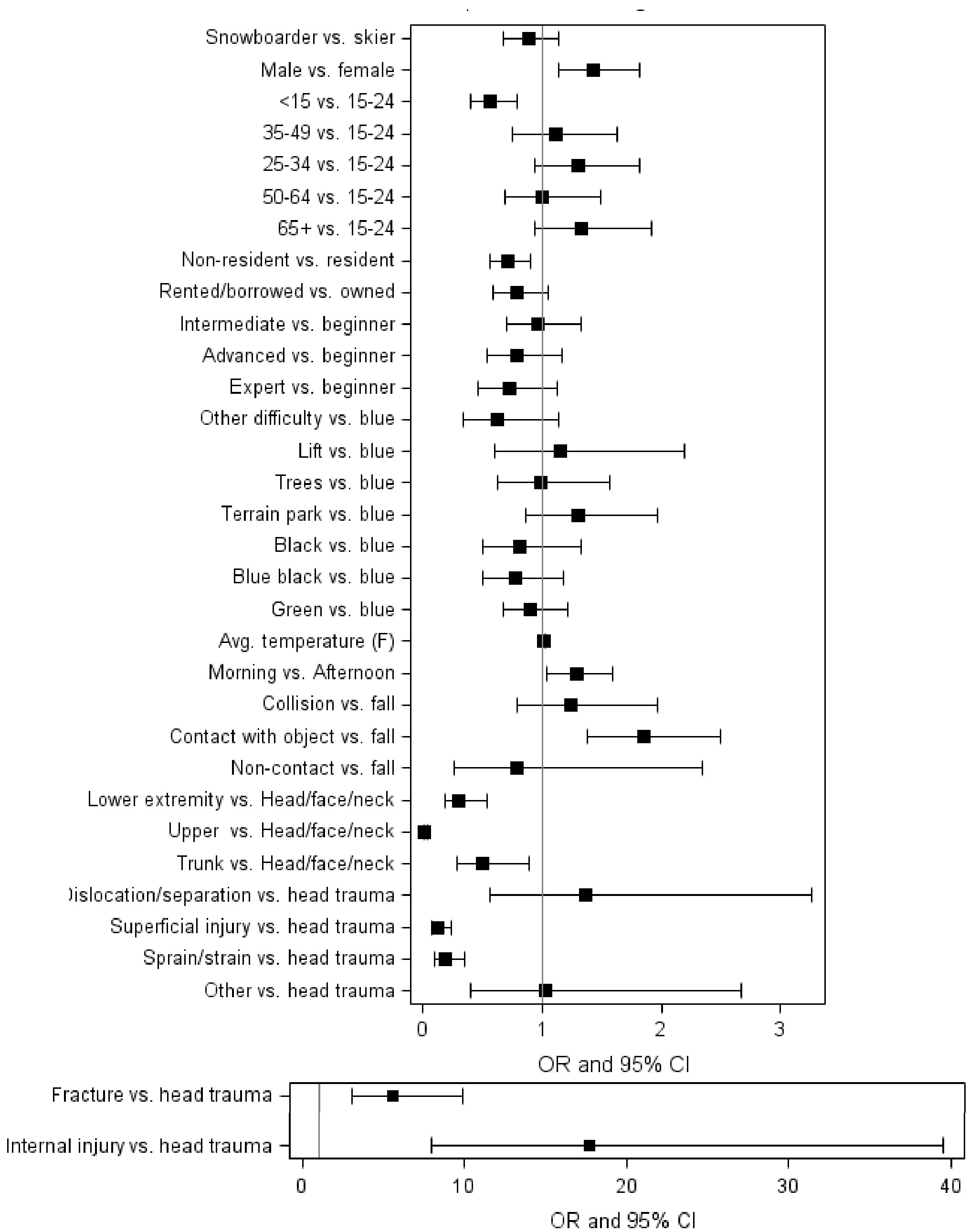
*OR = odds ratio, CI = confidence interval. Odds ratios represent associations between each factor level and body region, adjusted for all other factors in the figure.

Figure 6.2 Adjusted odds ratios and 95% confidence intervals for outcome of body region, Winter Park Resort, 2012/13-2016/17 seasons.



*OR = odds ratio, CI = confidence interval. Odds ratios represent associations between each factor level and injury diagnosis, adjusted for all other factors in the figure.

Figure 6.3 Adjusted odds ratios and 95% confidence intervals for outcome of injury diagnosis, Winter Park Resort, 2012/13-2016/17 seasons.



*OR = odds ratio, CI = confidence interval. Odds ratios represent associations between each factor level disposition, adjusted for all other factors in the figure.

Figure 6.4 Adjusted odds ratios and 95% confidence intervals for outcome of disposition, Winter Park Resort, 2012/13-2016/17 seasons*.

CHAPTER VII

DISCUSSION

The immediate goal of this research was to better understand injury rates and patterns among recreational skiers and snowboarders by examining a diverse set of intrinsic and extrinsic factors in a cohort of participants injured at Winter Park Resort, one the largest resorts in the U.S. The study aims arose out of the need to discover new areas of injury prevention for a winter sport population carrying a high injury burden. Despite decades of prior research, injury rates have been slow to decline, injury patterns remain mostly unchanged, and few effective injury prevention strategies have been implemented or evaluated at a population-based level. Understanding the interplay of unique factors not previously investigated and simultaneously evaluating their contributions is key to successfully tackling the challenge of injury prevention in skiers and snowboarders. The results from this thesis will directly contribute to the evidence base that informs decision-making surrounding safety at resorts, with the long-term goal of reducing the frequency and severity of skiing- and snowboarding-related injuries in Colorado and across the U.S.

The conceptual model presented in Chapter I, **Figure 1**, provides the framework for this thesis and emphasizes the importance of including both intrinsic and extrinsic factors in the study of sports injury etiology. Accordingly, the aims of this study were to quantify the univariate and independent effects of each proposed intrinsic and extrinsic risk factors on injury rates and patterns. To address the study aims and fill existing knowledge gaps in the field of winter sport injury, this research combined several sources of data rarely captured together to provide new information on how various risk factors contribute and interact to produce injury.

Overall the results of this research identified several important intrinsic and extrinsic risk factors and identified new areas for injury prevention efforts at the participant, clinician, and resort level. After adjustment for environmental factors, most intrinsic factors remained strongly associated with injury. Some environmental factors were expected to exhibit strong associations with injury, but adjustment for intrinsic factors demonstrated no significant effects. However, the environmental factors of snowfall, base depth, and snow conditions significantly impacted injury patterns and rates, generating ideas for prevention that can be immediately implemented at resorts. Further, practical lessons learned during data collection will help guide more efficient research and lay the foundation for future research. To synthesize the knowledge gained from this work, an overview of important study findings is presented followed by suggestions for evidence-based prevention efforts, strengths and limitations that should be considered, and concluding with future directions necessary to push the field of injury prevention for recreational skiers and snowboarders forward.

Intrinsic factors

A primary aim was to quantify the strength of associations between intrinsic factors and patterns of injury. Based on findings from prior research, it was hypothesized that most intrinsic factors would exhibit significant associations with injury in the Winter Park Resort population of skiers and snowboarders. As expected, age and gender were strongly and independently associated with mechanism of injury, injured body region, injury diagnosis, and disposition after adjustment for other variables and confounders. Taken together, these findings combined with past research indicate that 1) the relationships between age, gender, and injury are robust and should not be ignored when developing individual-level prevention efforts and 2) existing prevention efforts have not changed the landscape of injuries within these intrinsic risk factors, necessitating further research and more effective interventions.

When considering risk factors to target for injury prevention, it is essential to delineate between those that are modifiable and non-modifiable.[20] Sports injury interventions are more effective when targeting modifiable risk factors.[124] However, this does not imply that non-modifiable risk factors are unimportant. Identifying groups of individuals at increased risk is important for directing prevention strategies toward those with the greatest injury burden, with consideration of both frequency and severity. For example, the findings from this research indicate that prevention directed at young males would decrease injuries resulting from contact with objects. Similarly, ACL rupture prevention targeted at female skiers would be more effective than targeting male snowboarders at reducing rates of ACL tears.

Most of the injured population at Winter Park Resort were beginners and intermediate-level participants. Both skiers and snowboarders tend to overestimate their own ability level when evaluated against objective skill tests, indicating that an even greater proportion of the injured population at Winter Park Resort are beginners.[125] Injury researchers consider skill a non-modifiable risk factor, so like gender and age, prevention efforts should not be designed to change skill level (which can be achieved through lessons and practice) but applied specifically to each level. Beginners were less likely than advanced participants to be injured during collisions with people and objects compared to falling, which is likely due to an increased likelihood of falling compared to more advanced participants. Promoting techniques to reduce falls on blue (intermediate) runs would have very little effect in the advanced group, but may have a substantial impact for beginners. However, as discussed in Chapters IV and VI, implementing existing injury prevention efforts which protect the participant in the event of a fall (helmets, wrist guards) may be more effective at preventing injury than trying to decrease the frequency of falls in the beginner population.

Extrinsic factors

Skiers and snowboarders constantly interact with the resort environment. Participants must navigate variable snow, harsh weather, obstacles, other people, and difficult terrain. However, some days have clear visibility, few crowds, and freshly groomed runs. The environment is inextricably part of the causal pathway of injuries, and the potential for energy transfer resulting in injury is always present.[21] If extrinsic factors are better understood, modifications to the environment or adaptations to non-modifiable elements can be made for increased effectiveness of injury prevention measures.

This was the first study to incorporate daily participant denominator information into the calculation of injury rates for skiers and snowboarders. Prior studies reporting injury rates used resort seasonal totals, broader population-based numbers, or estimates from sports participation surveys as denominators. Although the number of participant-visits provided by resort management for this study were not stratified by individual characteristics such as gender or sport, they enabled calculation of daily injury rates allowing comparisons of rates by environmental condition. After controlling for other important environmental covariates and confounders, past 24-hour snowfall of <1 inch was associated with a 22% increase in injury risk compared to days with ≥ 1 inch, and hard pack conditions increased injury risk by 71% compared to powder days. These findings were robust in the presence of the potentially confounding effects of early season conditions consisting of little open terrain, low base depth, and high participant density. At Winer Park, there was no evidence that machine made snow increased injury risk, however other resorts in geographical locations that received less annual snowfall may rely more heavily on early season-snow making.

There are several implications based on these findings. The safety of participants patronizing the resort is affected by snowfall. Resorts should be aware of the increased risk associated with decreased snowfall and proactively take risk mitigation measures. Clinicians and ski patrollers can expect high volume patient loads on clear, warm days with little snowfall. Participants can apply the knowledge gained from these results and exercise caution during conditions associated with increased risk.

Public health context

One of the goals for the Centers for Disease Control and Prevention Healthy People 2020 vision is reducing sports-related injury treated in emergency departments (EDs), particularly sports-related traumatic brain injury.[7] Targeting winter sport participants as a part of the overall injury reduction strategy would help to achieve both goals, as skiers and snowboarders account for 600,000 visits to hospitals, EDs, and physicians' offices annually. Up to 20% of all ED visits are head injury-related. Injury prevention development can be guided using established public health frameworks to be impactful at the population level. There are numerous areas for injury prevention arising from the results of this study that can be operationalized in the context of the three E's of injury prevention: education, enforcement, and engineering (**Figure 7.1**).[126]

Educational interventions aim to provide information on risks and how to avoid them, change attitudes towards safer practices, or alter risk-taking behaviors and can be applied at the group or individual level.[127] The findings from this research indicate that participants should be educated about the effect of snow conditions on injury risk. Ski patrollers can personally interact with guests entering or exiting lifts to explain the increased injury risk, particularly collision-related injury, on days with less snowfall. This message could be directed more specifically towards skiers, who had greater odds of experiencing an injury due to collisions with people. Signs placed within plain sight of participants could warn of the hazards specific to weather conditions on particular days. Educational approaches have the potential to be effective but rely on uptake and implementation by each target individual. Due to the amount of individual effort involved, education is generally considered the least effective approach for injury prevention. Each ski resort in the U.S. has adopted a “Skier Responsibility Code”, which is a set of rules educating participants on risks of participation and individual responsibility for safe behavior at resorts. As discussed in Chapter VI, educational efforts have not been empirically evaluated at U.S. ski resorts, yet are widely promoted as effective avenues of injury prevention. Future studies assessing how education and knowledge influence behavior and consequently injury risk are warranted. The knowledge gained from this study, however, is important to disseminate to clinicians and ski patrollers who treat diverse groups of patients and have frequent opportunities to deliver educational messages regarding the highest risks relevant to specific patients and patient groups. Study information is additionally relevant to clinicians and ski patrol so they may anticipate injury burden and make informed decisions about resource allocation.

Enforcement refers to legislation.[127] Simply enacting rules and legislation at resorts suffers from limitations similar to education as individuals must choose to abide by the policies set forth, which is why legislation requires enforcement to be effective. Successful enforcement of existing rules may lead to behavior changes that decrease injury risk. For example, revoking ski passes as a consequence for excessive speeding may prevent collisions with people by deterring dangerous behavior. However, enforcement is often labor and resource intensive, and may not be practical in all settings. It is not feasible for ski patrol to be present on every run at all times to catch speeders, but identifying locations or times of day at increased risk would enhance efficient enforcement. A future evidence-based enforcement intervention derived from results presented in this thesis includes postponing the opening of ski runs until a minimum base depth is reached. For every 10-inch increase in base depth, injury rates declined by 8%. More work is needed to determine the exact threshold for opening and closing ski runs, but the current evidence suggests that defining a minimum would decrease injury rates.

Engineering refers to altering the physical or social ski resort environment in which the injury occurred for injury reduction purposes.[127] A main impetus for this research surrounded the idea that altering the resort environment would be more effective at reducing injury rates than targeting individual behaviors. Environmental approaches include injury reduction measures that are not dependent individual action; they are automatically and passively implemented and provide protective coverage to large populations. Unfortunately, environmental protective measures are generally overlooked as the physical environment is often viewed as non-modifiable. One of the most important findings from this research is that extrinsic factors, particularly snow and snow conditions, significantly impact rates and patterns.

The three E's can be implemented independent of one another but are most effective when elements from all three are included.[86] The following suggestions are interventions based on at least one of the three E's incorporating evidence gleaned from this study while considering prior research:

1. Groom snow more frequently to reduce injury rates. Injury rates are 71% higher on days with hardpack compared to powder. More frequent maintenance of snow may decrease hardpack.

2. On days with <1 inch of snow, participants should ski and snowboard cautiously and seek areas with groomed runs or softer snow to decrease injury rates and collisions.
3. Increase ski patrol presence on the hill on warm clear days to encourage safe behaviors.
4. Place signs to slow and direct traffic at intersections in order to decrease collisions with objects and other participants.
5. Establish a minimum base depth for opening or closing a ski run to decrease injury rates.
6. Increase uptake of wrist guard use and frequent binding checks to decrease the frequency of wrist fractures and knee sprains.
7. Increase uptake of binding checks through education and enforcement (for rental shops).
8. Mandate use of wrist guards and teach bindings checks during ski lessons.
9. Educate clinicians and ski patrollers of resort-specific injury rates and patterns so they may effectively disseminate information to participants.
10. Resort and ski patrol management should close or alter access to areas where participants consistently collide with objects to decrease both frequency and severity.

Limitations

There are several limitations that must be considered when interpreting findings from this research. The first and largest limitation is the lack of an uninjured comparison group, which prohibits conclusive statements about true injury risk at an individual level. Thus far, this limitation is widely observed across studies of skiers and snowboarders. At the time of completion of this research, there have been no published prospective epidemiological cohort studies of recreational winter sport participants in the U.S. that include an uninjured comparison group. Future research incorporating exposure information on uninjured participants is essential for determining injury risk and is discussed in the following section. Second, the true number of injuries in need of clinic treatment may have been underestimated. Participants who did not seek medical care at the clinic were not included. However, the proximity of the clinic from which injury records were obtained relative to Winter Park Resort increases the likelihood of capturing injuries requiring immediate clinical management; the nearest trauma center is located 20 miles from the resort, and the nearest Level I trauma center more the 60 miles from the resort. It is also possible that injured Colorado residents chose to seek medical care at their regular medical facility whereas out-of-state visitors may not have had other timely treatment options. Participants may have chosen to delay treatment if they did not perceive their injury to be serious. The study population may be biased to represent injuries that are more severe. Only one diagnosis per patient was included for analysis, underestimating the prevalence of some injuries. However, by including the first listed diagnosis, the most clinically important injuries (in the clinic physicians' opinion) were evaluated. Using disposition as a proxy for injury severity may have resulted in misclassification. Transferred individuals needed advanced imaging not available at the medical clinic for appropriate exclusion severe injuries, such as an intracranial hemorrhage. Information on ability, slope difficulty, and equipment ownership were only captured for patients presenting to ski patrol. We also only included patients from one resort, which may not be reflective of the experience of other resorts.

In 2016/17, the Denver Health medical system switched to a full EHR, fundamentally changing data collection. Instead of reviewing handwritten notes, many variables were available through automatic extractions. Body part, diagnosis, and helmet use were not available through automatic extraction and required record review to obtain, as in 2012/13-2015/16. The missing data rate for helmet use in 2016/17 was 4% compared to 10% for other seasons. The switch from handwritten notes to typed notes may have changed the way information was reported by clinicians. However, injury patterns did not differ significantly across seasons. Multinomial logistic regression assumes exclusivity of outcome categories, but some individuals sustained multiple injuries in one single event even though one was included. However, multinomial regression also assumes independence among observations which inclusion of multiple observations per person would violate. While not a true limitation, multinomial regression requires clear explanations of reference groups and careful interpretation. There are many unmeasured factors that likely influence injury patterns (e.g., alcohol consumption, behavioral characteristics, etc.), necessitating further research. Finally, these results represent an injured population from a single resort. However, Winter Park Resort is one of the most visited resorts in the U.S and it is the closest destination resort to a major international airport in Colorado, indicating inclusion of a diverse sample of participants.

Strengths

This research also has many strengths. One of the greatest strengths arises from the creation of the Winter Park Resort injury database. The database is a large, up-to-date, extremely rich source of clinically relevant winter sport injury information contributing to the novel aspects of this work and laid the foundation for future studies, discussed in the following section. There are certainly no publicly available datasets providing the quantity and quality of information on patients who sustained skiing- and snowboarding- related injuries. Few prior studies have used data from medical clinics located at the resort. The unique position of the clinic assured capturing of most injuries requiring immediate medical attention. The vast majority of prior studies include ski patrol-based injury data, and while there are advantages to this approach (convenience, less resource intensive), ski patrollers issue one general diagnosis (e.g., knee sprain) instead of specific diagnoses as presented in Chapter IV (e.g., grade III ACL rupture).

The large sample size collected over the course of 5 seasons allowed for testing of time trends and potential modification of injury patterns by sport. This study is the first to publish information incorporating daily denominator information into injury rate calculations. The weather information obtained from the resort was objective as opposed to measures of self-report, which can suffer from significant recall bias. The findings between environmental factors and outcome measures yielded actionable injury prevention interventions that can be implemented in the immediate future. The implications of these findings could extend beyond the Winter Park Resort population. Colorado is home to several destination resorts that experience similar snowpack and weather patterns. Altogether, this research is the first to combine several sources of data rarely captured together to provide a comprehensive analysis of skiing- and snowboarding-related injuries grounded in strong theoretical framework. Finally, answering novel research questions first on a small scale at one resort justifies more expensive and resource-intensive studies that can address injury risk. Therefore, while there are many limitations in this study, the benefit of answering new questions related to factors impacting injury rates is a major strength.

Future directions

To push the field of prevention in the winter sport population forward, robust study designs must be used incorporating uninjured populations and exposure information. One of the biggest challenges facing epidemiologists seeking to decrease skiing- and snowboarding-related injury rates is collecting high-quality information on uninjured comparison or control groups. Although difficult, this task is essential for understanding risk. Case-control studies estimating risk of specific injuries frequently use other injured participants as controls, which is problematic because injured control groups are not representative of the greater at-risk skier and snowboarder population as most falls at ski resorts do not result in injury. Some analyses included in this dissertation, while producing novel and high-quality information, also used injured groups of participants as the basis for comparisons. Prospective cohort studies are difficult to execute in transient large populations, such as skiers and snowboarders. Since the 10 million U.S. participants only average between 7 to 10 ski days annually per person, recruiting enough participants to detect meaningful changes in risk is extremely resource intensive in this setting, but not impossible and should still be pursued in new and innovative ways.[86] From an epidemiological standpoint, case-cross over study designs may be a potential compromise between resources and meaningful temporal information about environmental exposures.[21]

Despite the quantity of research on skiers and snowboarders, the true incidence of winter sport injury remains unknown due to a combination of factors. Each study conducted has its own resort-specific methodology, sources of data, or time frames, making comparisons across studies extremely difficult and external validity questionable. However, there is an overlooked solution that addresses these limitations more effectively than prior undertakings: implementing a national resort-based skiing and snowboarding-related injury surveillance system (ISS). Successful implementation of an ISS is challenging but necessary for forward progression and should be a priority of the organizations who profit from the millions of participants.

Injury surveillance is defined as the ongoing and systematic collection, analysis, interpretation and dissemination of health information.[128] ISSs can translate information into injury prevention action through the four-step sequence of sports injury prevention (**Figure 7.2**).[129] Most importantly, injury surveillance systems are the cornerstone of injury prevention from a public health perspective (Step A).[129] Basic information obtained from a ISS can answer the “who, what, when, and how” questions surrounding an injury problem and identify important risk factors (Step B) that inform the prevention measures introduced in Step C. Evaluating aspects of prevention programs can be achieved in Step D with an ISS that monitors trends on a weekly, monthly, or seasonal basis. Without first establishing a true baseline of injury incidence, it is very difficult to develop impactful injury prevention measures. Similarly, if an injury prevention measure is implemented on a population-based level without having first established a baseline for comparison, it is nearly impossible to evaluate effectiveness. In addition to providing the foundation for injury prevention efforts, ISSs can be instrumental in prioritizing clinical and financial priorities, which may be of greater interest to resorts than injury prevention alone. Ski patrols and clinics operate on limited funds, and may be able to use injury surveillance to argue for more resources such as additional medical supplies or more patrollers.

The U.S. does not have an established skiing and snowboarding injury surveillance system. Every 10 years, the National Ski Area s Association (NSAA) collects injury information from ski patrol report forms retrieved from 14 out of the nearly 500 operating U.S. ski resorts, selected based on resort size (number of annual participant-visits) and geographic region (East, Midwest, Rocky Mountains, West, Pacific Northwest).[7] These studies provide descriptive statistics and rates calculated from estimated denominators. While these studies have contributed important knowledge to the understanding of injury rates and patterns, the 10-year time interval between assessments and the precludes extracting meaningful information in a timely manner. A skiing and snowboarding injury and surveillance system would ensure timely dissemination of information to important stakeholders and standardize data collection procedures. Researchers, the NSAA, and resorts alike can be guided by previous successful examples of injury surveillance and their contribution to injury prevention efforts across diverse organizations.

In addition to the research knowledge gained from this study, there are practical lessons that can be applied to more successfully carry out future research. The database resulting from this study contains 100+ variables and is currently in use for clinical sub-studies and further investigations of specific injuries in greater detail than the presented epidemiological analyses. In addition to the deliverable of the final dataset, SAS code was produced to make prospective EHR completion of data collection more efficient and can be implemented on weekly basis if desired. Although most data fields are now available through online queries, there are no dedicated fields for diagnosis, body part, or mechanism of injury. SAS code has been created to automatically extract information from open text fields downloaded from the EHR system, drastically reducing work load. The average extraction time per record decreased from 2 minutes to less than 30 seconds, decreasing the workload for extraction of 1,200 cases (annual average) by 20 hours. The system of data extraction and collection allows researchers to continue to build the database more rapidly and conveniently, providing the framework for injury surveillance at Winter Park Resort. Finally, the results of this research will be disseminated to Winter Park Resort clinicians, ski patrol and resort managers, who are primary important stakeholders possessing the power to implement injury prevention at Winter Park Resort.

Conclusion

This dissertation has contributed new and meaningful information to the skiing- and snowboarding-related injury literature by evaluating the influence of intrinsic and extrinsic factors on injury rates and patterns using data collected from multiple sources at Winter Park Resort during five consecutive seasons. Both intrinsic and extrinsic factors significantly influenced injury patterns, and extrinsic factors significantly impacted injury rates. Several actionable areas for targeted injury prevention were identified, many of which can be implemented immediately. Information learned from this dissertation has the potential to reduce the substantial injury burden among skiers and snowboarders and has identified several areas for future research. Ultimately, results from this research will help reduce injury rates by providing evidence for interventions at the participant, clinician, ski patrol, and resort level.

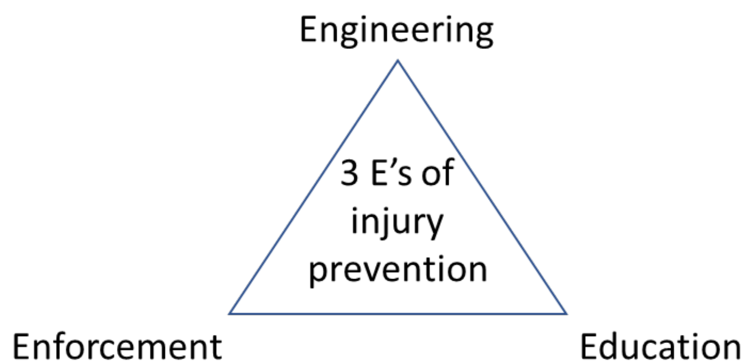


Figure 7.1 The three E's of injury prevention

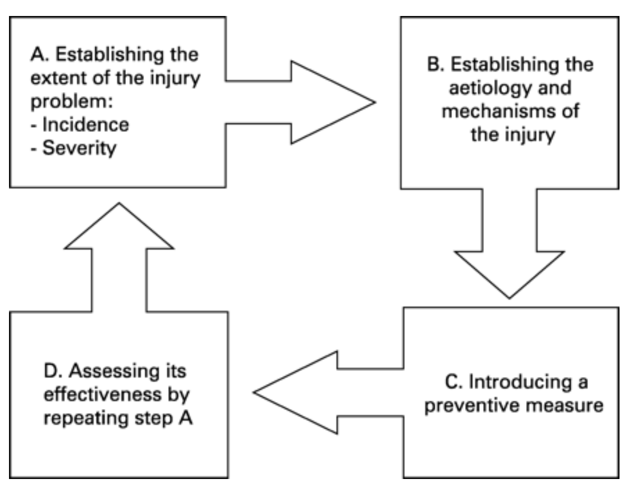


Figure 7.2 The Van Mechelen four-step sequence of injury prevention.

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