EDITORIAL

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Systems & Methods in Extreme Sports Medicine

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Extreme sports are associated with increased risk due to the inherently dangerous maneuvers performed, the environmental variables, and the distance from medical assistance. The majority of extreme sports disciplines were developed or popularized in the final decades of the previous century and are now practiced by millions of participants around the globe, from recreational adventure sports enthusiasts to elite athletes. Over the previous years the media has created grandiose spectacles of extreme sporting events, choosing to highlight crashes and the inflection points between risk and reward.

The mainstream media continuously reinforces the risk of these sports by reporting major injuries or fatalities. The extensive hours of training and safety protocol practice often takes a back seat during the coverage of extreme sports, creating a representation of inflated risk that seems insurmountable to the general population. Similar to other sports, extreme sports begin with the development of a fundamental set of basic skills before progressing to a riskier or a competitive version of the sport. Upon entry into extreme sports the first lesson is always to protect the environment and the safety of oneself. These principles are continually reinforced as the highest priority throughout every branch of extreme sports. As athletes progress into more challenging environments, both physical and psychological safety considerations follow a direct relationship with the amount of risk at hand.

The field of extreme sports is rapidly expanding with new and extreme versions of existing sports and the introduction of novel extreme disciplines. The rise in popularity and spread of legitimacy accompanied the introduction of extreme sports into the Olympics. The variety of extreme sports on land, water, and in the air, have merged to create multi-sport races that can take place over several days and a large geographical area. Whether it be competition against one another, against oneself, or a challenge with mother nature, extreme sports athletes approach the field with evident tenacity, experience, skill and determination. These unique circumstance are often associated with equally uncommon injuries that require specialized medical attention. Attention that is often common with more traditional sports.

The rapid increase of global participation in outdoor and adventure sports is associated with increased frequency of unique type of injuries. While the proportion of people who advance to a professional level remains low, the injuries affect every level of participation. Future research is further elucidating the predisposing factors and common mechanisms of injury to advance the safety of the sports alongside the advance of the sports themselves. The goal of extreme sports medicine research is to enhance the safety of the sports without compromising their exciting nature.

The complexity of these sports provides a framework that is best understood from within the field as first-hand experience. Additionally, participating in the activities provides an avenue to personally connect with athletes and obtain their approval for data collection and analysis. Being personally involved in the sports has fostered our motivation and benefited our research experience.

Our involvement in extreme sports continuously reinforces our drive to expand the medical knowledge surrounding the field. The relatively small amount of published literature provided an opportunity to amass a comprehensive text on extreme and adventure sports injuries. This issue combines elements of epidemiology, orthopaedics, engineering, psychology, physiotherapy and many other fields for a multidisciplinary perspective when approaching medical treatment of these injuries. Each chapter is written by a physician, experienced athlete or physiotherapist involved in the sport at an international level. Some chapters present new research while all chapters contain also a review of current literature. The research is presented from an academic viewpoint but is interpreted for the education of all those involved in extreme sports.

The editors aim to present this information for all those interested in treating or partaking in extreme sports. The hope is to bring the literature surrounding the various areas of extreme sports discussed into one volume. Within this review the common patterns and mechanisms of injury, treatment options and analysis of the psychological aspects are presented alongside the similarities and differences of each sport. Hopefully, this will provide useful information to those who enjoy and/or treat the fantastic world of extreme sports, and set a framework for future research to come.

ORIGINAL ARTICLE

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Injury Patterns and Wilderness Medical Preparedness in BASE Jumping

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SUMMARY

Background. The risks of BASE jumping are due both to its high inherent risk and the austere locations in which jumpers are often injured. Despite this, emergency management education and resources are lacking for BASE jumpers. We seek to highlight a category of treatable incidents whose outcomes could be improved through emergency medical education and training.

Methods. The available literature on BASE jumping injury profiles and wilderness medical education were reviewed. Based on these data, experts on BASE jumping injuries and austere rescue provide medical training and equipment suggestions for BASE jumpers operating in remote environments.

Results. Orthopedic injuries, particularly of the lower limbs and spine, predominate in BASE jumping. Almost no medical or training resources exist that have been developed for, or in partnership with, the BASE jumping population. Group preparedness may be significantly aided through a combination of equipment carried on each person and equipment that can be quickly accessed.

Conclusions. Emergency preparedness is multifactorial and context-dependent, but jumpers' ability to respond to both injury and rescue situations is crucial in the BASE environment. A proactive approach from the wilderness medicine community can address the problem of BASE jumping injuries from medical and pre-hospital perspectives.

KEY WORDS

Improvisation; parachutist; trauma; injury; BASE; Wingsuit

INTRODUCTION

Fixed object parachuting, also known as BASE (Building, Antennae, Span, Earth) jumping, is an extreme sport known to entail risk to life and limb (1,2,3). Regardless, the sport continues to grow quickly. Unfortunately, this growth is paralleled by an increasing number of BASE-related injuries and fatalities (3,4,5). To better remember and learn from these incidents, members of the BASE jumping community maintain a running list of information on all known BASE-related fatalities, known as the 'BASE Fatality List' (BFL) (4). The BFL contains information on each incident and clearly shows the upward trend in annual fatalities since the first known fatal incident in 1981 (**figure 1**). Even when accounting for the upward fatality trend, driven by the sport's growth and the increased popularity of wingsuit BASE jumping, significant variation in year-to-year fatality rates does exist and its causes are yet to be thoroughly understood (3,5).

The potential influence of social media, while not yet rigorously documented, appears anecdotally to be a driving force in riskier BASE practices. Recent advances in both the technology and popularity of wingsuiting, a discipline of skydiving/BASE involving a suit worn along with a parachute to increase glide, have accompanied this growth. Since 2000, wingsuit-related fatalities have gone from being sporadic to accounting for the majority of BASE-related fatalities (3,6).

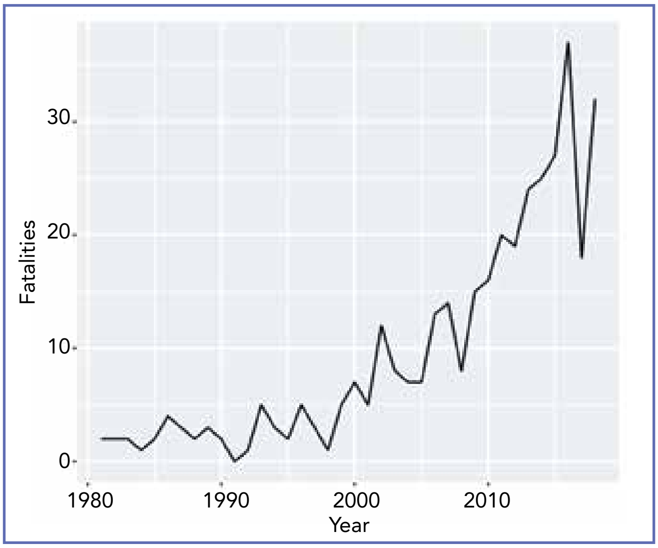

Figure 1. BASE Fatalities 1981-2018 (4).

Although not a formal rule, most BASE instructors recommend that aspiring jumpers have at least 150-200 skydives as a foundation of experience before beginning BASE training (7). This skydiving background helps develop a number of skills such as freefall and parachute piloting skills, planning, risk management, and emergency management.

A common assumption is that when one BASE jumps, only one of two outcomes is possible: either the jumper will be completely uninjured or immediately dead. However, many types of malfunctions are possible (7). Similarly, not all injured jumpers are either stable and ambulatory or dead on scene (2,5,6,9). It is possible that belief in this false dichotomy may itself be part of the reason that so little medical research exists regarding BASE injuries. Non-fatal injuries needing management do exist (2,5,6,9). Acknowledging the existence, and understanding the nature of treatable injuries is necessary to begin developing medical solutions.

With the growing participation and fatality rates in this sport, more research is required to understand the mechanism of risks associated with the sport and to better prepare participants and first responders (3). By evaluating the injuries and factors which lead to them in BASE jumping, standards can be established for the equipment needs of participants and medical responders.

METHODS

Review

A narrative review was performed through PubMed, Google Scholar and Google. Additional references were sought among citations within the articles. Search terms included "expedition", "skydive", "base", "jumping", "parachute", "injury", "wilderness", "medicine", "first aid", "training", "emergency", and "wingsuit". Articles identified in this search were included according to their level of discussion of wilderness medicine topics in the context of parachuting, focus on parachuting sports or parachute gear, and English language publication. Articles not focused on parachuting sports or on non-BASE parachuting were not considered for inclusion.

Suggestion development

Suggestions presented herein are representative of the consensus judgment of an expert panel based on injury profile data, evidence on wilderness medical kit contents and experience in field rescue with the guiding priority of minimalism. More specifically, the suggestions are crafted to solve the largest number of relevant problems with as little dedicated equipment as possible.

The experts consulted include the following: a US emergency medicine physician with 10+ years of BASE jumping experience who has worked as the expedition physician for many remote BASE expeditions, a US emergency medicine physician with 10 years of BASE jumping experience and 5+ years of experience as a remote expedition physician, a US military combat medic with 5+ years of experience in BASE jumping, a US military combat medic with 5+ years of experience in BASE jumping and wilderness EMS, and a professional BASE jumping instructors with 20+ years of BASE jumping experience. In addition to the listed qualifications, all experts have provided medical care and overseen rescues in the BASE environment.

Standardized questionnaires were given to every consultant and any additional information provided beyond the original questions was tracked and reported. The standard questions were the following.

- "What do you consider the bare minimum training and equipment for BASE jumper medical preparedness?"
- "What experience do you have in BASE medical emergency management?"
- "What has been your experience with using parachutes and other existing relevant equipment as improvisational tools?"
- "What do you see as a responsible way to provide medical training to jumpers?" The experts' various recommendations were recorded and grouped to develop the included suggestions as ideas for emergency preparedness equipment.

Results: expert panel

Each expert answered every question and their responses are summarized here with description of individual responses, when relevant.

Question 1: “What do you consider the bare minimum training and equipment for BASE jumper medical preparedness?” Regarding formal medical training, each of the following was mentioned as a recommended medical training pathway: Wilderness First Aid (WFA), Wilderness First Responder (WFR), Acute Trauma Life Support (ATLS), and Tactical Combat Casualty Care-All Combatants (TCCC-AC). None of these were mentioned more frequently than another.

Having enough experience in the BASE environment to anticipate and avoid accidents was consistently emphasized as being more important than medical training. Aspects of situational awareness, such as familiarity with local rescue vehicle access, how to activate local emergency and rescue resources, and the practice of agreeing on emergency plans prior to BASE activities, were similarly emphasized over individual medical training. The ability of a jumper to lower themselves from a suspended position, referred to as “self-belay”, is considered a mandatory skill for BASE jumpers by one expert.

Regarding equipment for medical preparedness, the experts consistently emphasized the importance of considering context (location, weather, team size, time of day) of any given jump or expedition. The most commonly suggested items to be carried were tape, multitools, dental floss, knives, methods for locating a team member (GPS locator or whistle), tourniquets, and water. Other items mentioned include SAM (Structural Aluminum Malleable) splints, traction splints, blankets and safety pins. Multiple experts noted that there is an important difference in what equipment needs to be 1) carried on each individual jumper, 2) carried on at least one person in the team, 3) quickly accessible by the team, and 4) accessible through external resource activation, such as rescue teams. Small items and those regarding improvisation and self-rescue, such as water, dental floss, tape, and multitools, were recommended to be carried by each jumper. Larger sets of equipment, such as climbing equipment for vertical rescue, traction splints and backboards, simply need to be reasonably accessible by the team.

Question 2: “What experience do you have in BASE medical emergency management?” BASE jumping-related incidents in pre-jump activities, jumping activities and post-jump activities were described. Injuries before or after BASE jumping activities were typically related to hiking and climbing while approaching or climbing down from the exit point or landing areas. BASE jumping incidents managed by, witnessed by, or otherwise involving the consulted experts include the following: cliff and building strikes, some resulting in vertical entrapment on the object’s vertical face; hypothermia, frostnip, and frostbite; heat stroke and dehydration; fractures of the wrist, radius, ulna, fingers, nose, vertebrae, ribs, femur, tibia, and ankle; dislocations of the shoulder, knee, patella, and ankle; improvised high-angle rescues from cliffs; the placement of backboards with and without BASE jumping rigs and helmets; water rescues; and placement of femoral traction splints.

Question 3: “What has been your experience with using parachutes and other existing relevant equipment as improvisational tools?” Experts’ experience with developing splints for orthopedic injury of the tibia, ankle and wrist were described using common protective gear (such as shin pads), parachute lines and extra clothing. Slings were developed from jumpers’ clothing using safety pins that one expert regularly keeps in their BASE jumping equipment. Dental floss carried by a jumper has been used in an incident managed by one expert to lift water and climbing equipment to a vertically-entrapped jumper. One expert has used a piece of rigid cloth from the parachute deployment system known as the ‘bridle’ to develop a tourniquet and used their multitool as a windlass for tightening the tourniquet. The use of parachute equipment in marking landing areas for a rescue helicopter was also mentioned.

Question 4: “What do you see as a responsible way to provide medical training to jumpers?” All consulted experts agreed that providing small amounts of medical training to individuals otherwise lacking medical training may be harmful. This risk may exist in the form of partially-trained individuals failing to activate emergency resources out of the assumption that their limited training will be adequate to manage a given emergency or improperly applying their skills. This possibility also may introduce liability concerns for those offering the training. Most experts recommended that any medical training provided must be as simple and limited as possible with the priority placed on timely activation of emergency resources and patient assessment. Encouraging jumpers to seek medical training through some type of established formal training (WFA, WFR, TTTC, etc.) was broadly considered the most responsible approach by the consulted experts. No particular training pathway or program was mentioned with more consistency than another.

DISCUSSION

Accident rates

BASE jumping environments are quite heterogeneous, so a jump’s absolute risk is unpredictable. Factors like exit altitude, the landing area, changing weather, and social pressures provide meaningful stressors and distractors that intensify the variability in risk between jumps, while variability in (changing) technical challenges has direct impact on the jump's outcome. Despite this diversity, the injury rate has been predicted independently by various authors at 0.4% per jump (1 injury per ~250 jumps).[1,9] Severe injuries, defined in the study by the time needed to recover, occur at a rate of 0.2%, or 1 severe injury per 500 jumps (6).

One popular BASE jumping location, Norway's Kjerag Massif, has tracked the number of jumps made since 1994 resulting in a fatality risk of 0.04%, or 1 in ~2500 jumps at this object (1). Kjerag Massif is generally considered a "safe" object due to the forgiving cliff angle, ample freefall altitude, legality, and landing areas. Other BASE jumping locations are therefore likely to be at least as dangerous, if not more dangerous, in terms of fatality risk per jump. These accidents, fatal and non-fatal, provide an ongoing challenge for medical providers and search-and-rescue resources in popular jumping locations: Italy, Switzerland, Norway, Australia and the Western United States currently most notable.

Injury profiles

Injuries with all varietiesy of intensity occur within BASE jumping. **Table I** stratifies a sample of reported BASE jumping injuries by representative injury type and severity, as determined by time to recovery, risk of death and level of medical care required in managing the injury (9).

Regarding anatomic injury profiles, lower limb injuries are the most commonly reported—present in 61-72% of BASE accidents due to being the first body part to "hit the ground" and slow down the flying jumper upon impact (6,8). Of the other injuries documented, 20-31% included back and spine injuries, occurring when the legs do not absorb all the energy of an impact; 18% included chest wall injuries, often related to hitting vertical objects under canopy or on landing; 18% included upper limb injuries, commonly from landing on an outstretched hand; and 3-13% included head trauma from landing or object strikes. Many subjects reported multiple injury categories per incident. Søriede and colleagues indicate that severe head trauma was the most prevalent fatal injury in

Table I. BASE Jumping Injury Severity Diversity (9).

Mild (25.6%)	Moderate (43.6%)	Severe (30.8%)
Contusions Small lacerations Strains and Sprains	Small bone fractures Joint dislocations Blunt thoracic trauma	Femoral fractures Open fractures Multiple moderate injuries

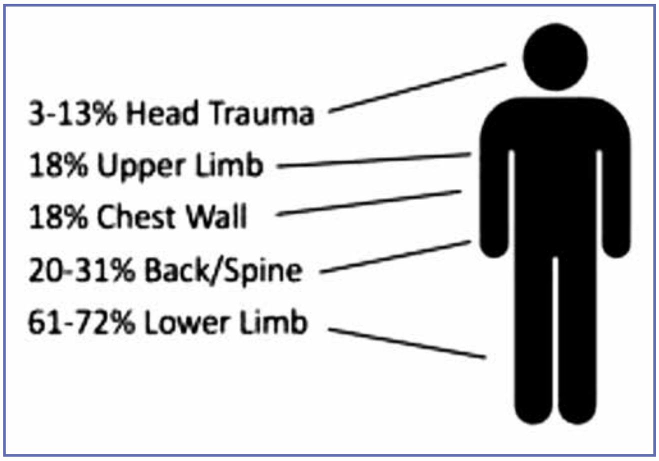

Figure 2. Dispersion of Injury Regions in BASE Jumpers (6,9).

their sample from the Kjerag Massif jump records (1). These studies' injury data are presented in **figure 2** and represent the relative rates of body region inclusion, meaning that more than one may be marked for any given jumper or injury, leading to a cumulative rate appearing to exceed 100%.

Research on BASE jumping injuries using emergency department records gives further resolution to the data. From 2010-2014, BASE jumping injuries treated in United States emergency rooms were diagnosed with injuries in multiple body regions in 55% of cases, 38% with isolated extremity injuries, 5% with isolated head or neck injury, 2% with isolated chest injury, and 1% with isolated abdominal injury (10). It is worth noting that in analysis of BASE jumping injuries in this study, all patients that reached an emergency room ultimately survived their injuries, whether they were discharged directly from the emergency room or escalated to inpatient or surgical care.

The jumpers' experiences and mindset

Safe practices, conservative risk assessment and humility are considered by the consulted experts to be capable of preventing many of these accidents. However, of BASE jumpers surveyed in Mei-Dan and colleagues' 2012 work, 43% had experienced a significant injury in the sport, 72% had witnessed the death or serious injury of a fellow jumper, and 76% had had what they considered to be a 'near-miss' incident (6). Only 6% of jumpers surveyed had never been injured, seen a fatality or had a 'near-miss.' In addition, based on Mei-Dan and colleagues' analysis of the known fatalities and their data-driven estimate of the number of active BASE jumpers, it was estimated that there is approximately a 10% lifetime fatality risk associated with BASE jumping (3).

Even among other extreme sports, BASE is a uniquely risky environment (11). For this reason, the psychology of BASE jumpers has also been the subject of research. Understanding their motivations for becoming involved in the sport may contain insights for how to motivate them in pursuing further training in related topics like emergency management. Scientific personality assessments among BASE jumpers have identified high levels of novelty-seeking and self-directedness with low levels of harm avoidance, social reward dependence and self-transcendence, when compared to controls (12). However, no narrowly-defined personality profile encompasses all jumpers. Individual variance in personality traits does not significantly correlate with a history of BASE-related injuries or jumpers' gender identity (12,13). Significantly, 40% of BASE jumpers were found to have extremely low harm avoidance scores, while only 5% of controls had comparably low scores.[14] These low harm avoidance scores may confer resilience to psychological stress and are edified by high levels of persistence and self-directedness (14).

Analyses considering these personality traits alongside neuro-endocrine stress markers have identified latent subgroups of stress reactivity patterns and distinct personality profiles among BASE jumpers (14). Stress reactivity trajectories surrounding BASE jumps correlated significantly with these multidimensional personality profiles and individual personality measures. Jumpers' experience, personalities and mindset do concretely affect the stress their body undergoes and the way they experience the jump.

The colloquial assumption is often that BASE jumpers have little regard for their own lives and enjoy risk itself. However, their motivations are far more complex. Wingsuit BASE jumpers in a particularly risky discipline called terrain proximity flight—intentional flight close to the object—have been the subject of qualitative psychological assessment (15). BASE jumping was found for these individuals to be an extremely personal pursuit. It was their way to understand and process the world, grow as individuals and discover their authentic selves. They described it as instilling confidence, a sense of purpose, emotional regulatory capacity, and the ability to manage fear and anxiety in all facets of their lives. They saw wingsuit BASE jumping not a risk taken just for the thrill, but a mechanism of growth and self-realization (15).

These data help show not just what kind of people are drawn to become BASE jumpers, but also how their training and experience interact with and contribute to who they become and how they handle the physical and psychological stresses of BASE jumping. This may serve as an important context for the development and promotion of BASE-related training programs, such as an emergency management course.

Wilderness medicine considerations and training resources

While new jumpers (skydivers and/or BASE jumpers) are typically encouraged to seek some sort of first aid training, it is not known whether this training is obtained with any regularity. Based on the authors' experience and personal communications with many BASE jumping course instructors, as of this writing, it is not common practice to offer medical training as a formal component of BASE training programs, if it happens at all. BASE jumpers are often insufficiently trained and ill-outfitted for medical emergencies. Integrating medical and emergency management training components to first BASE jump training courses could be a way to systematically address this gap among jumpers entering the sport.

No research articles were identified that involved the documentation, development, effectiveness, or necessity of any wilderness or improvisational medical interventions aimed specifically at skydivers, wingsuiters or BASE jumpers. One article mentioned a parachute as a potential improvisational tool, but did not demonstrate gear-specific knowledge or application (16). Case reports about injured jumpers also exist, but offer little in terms of solutions (17, 18). A book on extreme sports injuries mentioned some preliminary considerations for treating injured BASE jumpers and skydivers, but was not intended to meaningfully prepare the jumpers themselves (2). The only identified resource developed specifically for jumpers is an extended post on a popular BASE jumping social media forum covering the absolute basics of emergency assessment, shock, blood loss, long bone injuries, and joint injuries for BASE jumpers (19). *The Great Book of BASE,* the popular training guide for the basics on BASE jumping, lacks specific advice other than the blanket advice to seek first aid training.[20] Neither an overview nor recommendations on what medical equipment should be carried on BASE jumping expeditions was identified in the authors' search.

Existing work does acknowledge the question of which items belong in a medical kit, but often focuses broadly on what items have been carried on expeditions in the past (21-23). Some authors have curated their recommendations to the problems faced by a specific group of athletes, such as mountain climbers, adventure race participants and backcountry snowboarders (24-30). These medical kits tend to focus on managing soft tissue injuries, minor orthopedic injuries and repetitive use injuries. Articles on sports practiced in less accessible locations did have a stronger focus on tools that would aid evacuation or rescue, such as whistles and GPS, and improvisation, such as binding materials like wire and tape (27,28).

Jumpers are not likely to be searching for their training solutions in the medical literature, so these limited academic results are unsurprising. Currently, new jumpers only have informal stories about managing injuries, very limited first aid training, and potential career medical training to inform the dangers they may face in the sport. Discussion and action within the medical community could very realistically lead to the development of tools, resources, or training that affect real progress in BASE jumper emergency preparedness.

Even among those who do not survive their BASE jumping injuries, about 12% of fatally injured jumpers were alive on site when rescuers arrived.[8] While this does not mean that any individual case certainly could have been affected through improved interventions, it indicates the existence of potentially treatable cases. Details of the 'golden hour' are controversial in the scientific literature, but simple actions that can be taken in-field or training that can be given to expedite rescue and escalation of medical care are likely to be beneficial (31,32).

It has been shown that with adequate initiative, a sport's cultural push for safety can lead to concrete outcomes. For example, avalanche survival courses have recently become very popular among alpine and backcountry skiers. Even without regulatory compulsion, those athletes have taken their safety into their own hands, with preparation such as first aid courses being pre-requisite for many professional avalanche training courses. Similar educational resources do not exist for skydivers and BASE jumpers. Improvisational medicine based on parachute equipment appears entirely unaddressed in the civilian literature on wilderness medicine. Although the authors are aware of the military literature on improvised medical uses of parachute equipment, further work needs to be done adapting these principles to civilian BASE jumping activities (33).

Medical kit suggestions and preparedness recommendations

Based on the injury profiles developed in this previous research (**figure 2**), it is clear that injuries of the lower limb predominate in BASE jumping, followed by back and spinal injury, chest wall injury, and upper limb injury. The treatment of orthopedic injuries is therefore of highest priority for equipment and training selection purposes. Existing data on the contents of professional medical rescue kits indicate a prioritization of equipment for splinting, resuscitation, oxygenation, wound dressing, and heat management—a higher level of care than can be reasonably achieved in an individual emergency kit (23,25,34). The following suggestions do not represent an exhaustive or ideal list. Self-management of medical problems should only be considered in the absence of accessible rescue care as a measure of last resort. A 'fully prepared' jumper would need to have dedicated training and bring additional equipment, similar to skiers or climbers heading to remote unknown dangerous projects, but simplicity drives adherence. It is important that each and every person in the jumping group agrees on a concrete, current plan on which emergency resources to contact and how they will be contacted for every jump location, known as "exit points", and region. Jumpers must consider that intervening circumstances can make emergency access impossible. For example, rescue helicopters often will not fly in fog. This means that even with a perfect plan for rescue, there are instances where some degree of self-management is necessary. It is wise for BASE jumpers and anyone recreating in remote environments to seek some degree of training in first aid and wilderness emergency management.

No data were identified regarding what medical gear best supplements standard BASE equipment for the management of medical emergencies. The authors and consultants therefore share their personal clinical practices. A data-based approach is categorically superior to a compilation of opinions, so the available data on wilderness medical kit contents were incorporated whenever possible, but the unique practicalities of and severity of injuries in BASE jumping limited these resources' contributions (23,35-37).

The consultants' experience indicated that BASE jumpers deciding on medical kit contents should consider both Primary equipment, carried redundantly by each jumper, and Secondary equipment that should be available for use, but does not need to be carried on each person. The treatment of orthopedic injuries, enabling improvisation with minimal equipment, and aiding cliff/building rescue were considered the top priorities based on the presented data and the consultants' experience. Items that are highly recommended as Primary equipment include an emergency whistle and/or a GPS beacon, a small roll of tape, a multitool, dental floss, and extra water (**table II**). These represent items with important roles not just through their intended functions, but also the improvisational and rescue techniques that become possible through them. The whistle is to aid in locating the injured jumper, tape and a multitool can have a wide number of improvisational and survival roles, dental floss can be lowered to retrieve the end of a heavier rope or light supplies in rescues where the victim is vertically suspended (stuck in tree, hung up on a cliff), and extra water is a survival aid in any situation where prolonged rescues are a possibility. Depending on situational context, a GPS locator such as Garmin InReach should be considered for inclusion in the Primary equipment. It is reasonable to substitute a lightweight utility cord for dental floss, if kit size permits, but jumpers must be strictly cautioned against the likely severe or fatal outcome of suspending their own body weight on any unsuitable type of cord.

Secondary equipment is usually kept in a nearby camp or vehicle and typically includes items such as SAM splints, femoral traction splints, blankets, and extra water, in addition to equipment for other location-specific concerns like cliff and tree rescues. Some consultants recommend the inclusion of a pelvic binder if members of the group are trained on its proper use. In any discussion of wilderness medical care, it is important to address the idea that treating a potential future patient beyond the scope of one's training can be just as dangerous as not acting. Adequate training is key to the responsible and effective practice of wilderness medical care. Unique needs presented by environmental and personal contexts should absolutely be considered by all jumpers when making equipment decisions.

Improvised solutions like carrying techniques, slings, splints, and rescue techniques are all made much more viable with even minimal equipment such as these. While it may seem counterintuitive, rigid supplies and classic tools (i.e., SAM splints) are not necessary to make an effective splint. Padding materials, such as a parachute or wingsuit arm foam, are quite rigid when adequately compressed. For this reason, rigid splinting and support materials like sticks or hiking poles are not strictly necessary for field injury management of common BASE-related orthopedic injuries. No matter the supplies, each environment presents different challenges. Just to name a few examples, jumpers in cliff and forest environments would be well-served to learn rappelling techniques; in the afternoon, bringing a headlamp is a must, given the long duration of some rescues or paths off the object if conditions deteriorate; and extra water is more crucial in desert environments where water is unavailable or where filtering may not be feasible. In any location, having a long-term mindset with one's contingency plans is advantageous.

Anecdotally, recent incidents have highlighted the importance of bringing equipment that can aid in locating an injured jumper. One in particular involved a wingsuit pilot who survived terrain impact without deploying a parachute. The jumper was severely injured but was not located for many hours until hikers heard them yelling. Simple emergency whistles carry better than the human voice over distance and a carried GPS beacon could have called for rescue. Either may have significantly expedited rescue for this jumper or another in their situation.

Table II. Suggested equipment.

Primary Equipment	Secondary Equipment
Emergency Whistle	SAM Splint
Tape Roll	Femoral Traction Splint
Multitool	Blankets
Dental Floss	Extra Water
Extra Water	Pelvic Binder
GPS Locator (per context)	Vertical Rescue Equipment

LIMITATIONS

The primary limitation of these suggestions is the lack of identified experimental data on what constitutes the optimized BASE medical kit. Unfortunately, identified data on medical kits in other wilderness and sport environments are difficult to generalize to BASE because of its unique weight/volume considerations, injury profiles, and improvisational tools in the BASE environment. To mitigate this, many consultants with broad experience in BASE expedition medicine, injury management, and search and rescue were consulted.

CONCLUSIONS

Best practices in wilderness medical emergencies depend heavily on the medical background of the jumpers, the severity of the situation, and location. Despite these nuances, with modest preparations, many BASE emergency situations could be made more manageable and lives can ultimately be saved.

Orthopedic injuries, particularly of the lower limbs, are the most likely in BASE jumping. Limited equipment with both medical and rescue-oriented purpose carried by each jumper may help improve BASE jumping accident outcomes, in the opinion of consulted experts. The suggested equipment includes primary equipment carried redundantly on each person and secondary equipment that is accessible to the team, but is not practical or helpful to carry on the person.

Care must be taken to provide and develop training in a 'do no harm' fashion, avoiding improper application of only the most memorable techniques in damaging ways by partially-trained individuals. The potential liability concerns associated with any medical training must be acknowledged, but can be mitigated and should not stand as an unquestionable barrier.

The development of curricular materials for teaching emergency management educational sessions at BASE jumping holidays ("Bridge Day" in West Virginia, for example), skydiving events, BASE first jump courses, and BASE advanced jump courses therefore may represent opportunities to affect injury outcomes in the entire parachuting community. Resources should be developed for audiences with and without formal medical training.

BASE jumping carries significant risk, but the BASE community as a whole also demonstrates a dedication to safety. A population-centered approach to determine jumpers' needs will aid in designing effective solutions and curricula. There are significant challenges presented by the wilderness environments in which BASE jumpers are often injured, but creating links between the BASE and wilderness medicine communities could lead to changes with concrete impact on injury and fatality outcomes. This work serves only as an early step in establishing best practices for jumper preparedness.

CONTRIBUTIONS

Study concept and design (JS, GV); Acquisition and analysis of data (JS, MS); Drafting of the manuscript (JS); Critical revision of the manuscript (JS, MS, GV, OM); Approval of final manuscript (JS, MS, GV, OM).

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (38).

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Use of a Prospective Survey Method to Capture a Picture of Overuse Injuries in Kitesurfing

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SUMMARY
Background. Kitesurfing is one of the world's fastest growing Olympic aquatic sports. However, previous scientific literature on this sport has mainly focused on acute injuries. The aim of this study was, therefore, to capture a picture of the burden of overuse injuries in kitesurfing.
Methods. Active kite-surfers regularly completed an online questionnaire, describing the health of their shoulders, lower back and knees as well as any injury related symptoms.
Results. Forty-three participants completed a total of 304 questionnaires, covering a total period of 2,096 distinct person-days. Person-days of reduced participation related to shoulder, lower back and knee problems were 8 %, 3% and 8% of the total respectively. Performance was affected related to shoulder, lower back and knee problems in 11%, 22% and 16% of person-days respectively.
Conclusions. Overuse injuries emerged as an important predictor of reduced participation, decreased performance and discomfort in kitesurfing. The prospective survey method captured a picture of overuse injuries in kitesurfing not previously described.

KEY WORDS
Aquatic; body mass index; knee; participation; questionnaire; shoulder

INTRODUCTION

Kitesurfing is amongst the world's fastest-growing Olympic aquatic sports, and with a global participation of 2.8 million participants, it is becoming a mass sport (1). Participation is increasing at both amateur and professional levels, among both males and females, predominantly between the ages of 18 and 45, but children and adolescent participation is also rapidly growing (1). Kitesurfing has recently been included in the Olympic programs as well. It made its first appearance at the 2018 Youth Olympic Games in Buenos Aires, Argentina and will be included in the 2024 Paris Olympic Games (1).

Kitesurfing is considered a high-risk activity, and the available scientific literature on this sport focuses mainly on acute injuries (2-9). However, available epidemiological data are quickly outdated and do not account for the rapid evolution of kitesurfing equipment. While scientific studies report the loss of control of the kite as the leading cause of serious injuries (2-4, 9 -12), this occurrence has become rarer thanks to the introduction of the quick release systems at the beginning of the 21st century. Additionally, total-depower kites (widely adopted from 2005 onwards), allow the kiter to eliminate the pull of the kite by merely letting go of the bar (13). Strategies to improve safety and reduce the incidence of acute injuries have been also developed (14-16). For example, since 2019, it has become mandatory to wear a helmet and impact vest during competitions (1). It was implemented in response to many early reports of kitesurfing trauma involved boards recoiling at the kitesurfer by the elastic board leash (12,13). Kitesurfers may also lose control of the kite during flight and suffer cranial trauma when landing back on their board (17) or being thrown against an obstacle (4). Outside of competition, however, the use of protective equipment has been reported to range from less than 30% among injured North Sea kitesurfers, to 56% of practicing Portuguese kitesurfers (18).

While much has been done to reduce acute injuries, overuse injuries have yet to be described, despite suggestions that overuse injuries may be a significant cause of reduced performance and morbidity in kitesurfing. In recent years, an increase in competition performance has led to the development of professionalism and a general intensification of training. As seen in traditional activities, the protracted repetition of maneuvers during training may lead to a functional overload of the musculoskeletal system. In addition, the high speeds maintained by the kiteboard over the irregular surface of the water exposes the whole body to high levels of vibration, which may produce overuse injuries (9, 19).

The aim of this study is to capture a picture of the burden of overuse injuries in kitesurfing.

Overuse injuries have been defined as traumatic injuries, without a single, identifiable injury responsible for the event, but caused by repeated microtrauma (20). Overuse injuries are probably under-recorded, even in more traditional sports, due to the lack of medical personnel available to examine athletes on a daily basis, the time-loss from sport injury definition, and through the use of retrospective studies (21). For these reasons, we applied to kitesurfing the focused-on-symptoms approach validated by Clarsen *et al*, for the registration of overuse injuries in different sports, including cross-country skiing, volleyball, floorball, road cycling and handball (22).

METHODS

Participants were recruited through social media with one of the following criteria: having a kitesurfing focus or being linked to an Italian geographic area which is associated with kitesurfing. Each month, participants received an invitation, in Italian, to complete an online survey. The questionnaire collected data regarding injuries of the shoulders, lower back and knees, and whether the injuries were from kitesurfing or another cause. Specifically, four questions (originally in Italian) were asked:

1. have you had any difficulties participating in normal training and competition due to shoulder/low back/knee problems during the past week?
2. To what extent have you reduced your training volume due to shoulder/low back/knee problems during the past week?
3. To what extent have shoulder/low back/knee problems affected your performance during the past week?
4. To what extent have you experienced shoulder/low back/knee pain related to your sport during the past week?

We excluded non-kitesurfing related injuries and separated acute from overuse injuries in the dataset based on telephone interviews by a sports physiotherapist. The self-reported number of hours spent practicing kitesurfing was collected, as was the main kitesurfing discipline each participant engaged in. At the completion of the study, each participant self-reported age, sex and body mass index (BMI, in $kg \cdot m^{-2}$). Approval to conduct this study was given by the institutional Ethics Committee of the second author and all participants gave informed consent.

ANALYSIS

Data were collected electronically and compiled in an MS® EXCEL spreadsheet, then imported into SAS (Statistical Analysis Software, Cary, NC) version 9.4 for analysis. Means are reported with standard deviations and, where data was not normally distributed, medians are reported with interquartile ranges. Relationships between the binary status of having reported an injury or not, and having reported a serious injury or not, were tested for association with BMI using logistic regression (PROC LOGISTIC).

RESULTS

Forty-three participants (age: range 21-55, mean: 39, SD: 8.9; BMI: range 15-19, mean: 23 SD: 2.8), engaged in three different disciplines (i.e. freestyle, course racing, wave riding), completed 304 questionnaires. Ten (3%) of these questionnaires were completed within a week of completing a previous questionnaire, with a total of 38 person-days of additional coverage, instead of 70 days since a previous questionnaire was completed. Therefore, the total period covered by completed surveys was 2,096 distinct person-days. Of those, 1,807 (86%) were kitesurfing days involving males (6/43 participants were female, 14%). Median time spent kitesurfing during the previous week was 5.5 hours (IQR 2.5-10). The number of person-days associated with reported problems for shoulders, lower back and knees are shown in **table I**.

The number of person-days associated with reduced training volume due to reported problems for shoulders, lower back and knees are shown in **table II**.

The number of person-days associated with affected performance due to reported problems for shoulders, lower back and knees are shown in **table III**.

Table I. Number of person-days for each type of participation related to shoulder, lower back and knee problems (n=2,096).

	Participation	Shoulder n (%)	Low Back n (%)	Knee n (%)
Kitesurfing related	Full participation	1,851 (88.3)	1,447 (69.0)	1,481 (70.6)
	Full but with problems	28 (1.3)	490 (23.4)	7 (0.3)
	Reduced participation due to problems	14 (0.7)	56 (2.7)	483 (23.0)
	Cannot participate due to problems	147 (7.1)	0 (0)	56 (2.7)
Not kitesurfing related	Full participation	28 (1.3)	68 (3.2)	35 (1.7)
	Full but with problems	21 (1.0)	21 (1.0)	70 (3)
	Reduced participation due to problems	0 (0)	7 (0.3)	0 (0)
	Cannot participate due to problems	0 (0)	7 (0.3)	0 (0)

Table II. Number of person-days for each type of training volume related to shoulder, lower back and knee problems (n=2,096).

	Reduced training volume?	Shoulder n (%)	Low Back n (%)	Knee n (%)
Kitesurfing related	None	1,901 (90.7)	1,685 (80.4)	1,608 (76.7)
	Minor extent	118 (5.6)	253 (12.1)	229 (10.9)
	Moderate extent	21 (1.0)	48 (2.3)	77 (3.7)
	Major extent	0 (0.0)	0 (0.0)	7 (0.3)
	Cannot participate due to problems	0 (0.0)	7 (0.3)	21 (1.1)
Not kitesurfing related	None	49 (2.3)	89 (4.2)	107 (5.1)
	Minor extent	0 (0)	0 (0)	47 (2.2)
	Moderate extent	0 (0)	0 (0)	0 (0)
	Major extent	0 (0)	14 (0.7)	0 (0)
	Cannot participate due to problems	0 (0)	0 (0)	0 (0)

Table III. Number of person-days for each type of affected performance related to shoulder, lower back and knee problems (n=2,096).

	Affected performance	Shoulder n (%)	Low Back n (%)	Knee n (%)
Kitesurfing related	None	1,824 (87.0)	1,538 (73.4)	1,552 (76.7)
	Minor extent	167 (8.0)	365 (17.4)	258 (10.9)
	Moderate extent	49 (2.3)	83 (4.0)	104 (3.7)
	Major extent	0 (0)	7 (0.3)	7 (0.3)
	Cannot participate due to problems	7 (0.3)	0 (0.0)	21 (1.1)
Not kitesurfing related	None	35 (1.7)	75 (3.6)	98 (4.7)
	Minor extent	14 (0.7)	14 (0.7)	56 (2.7)
	Moderate extent	0 (0)	0 (0)	0 (0)
	Major extent	0 (0)	7 (0.3)	0 (0)
	Cannot participate due to problems	0 (0)	7 (0.3)	0 (0)

The number of person-days associated with pain due to reported problems for shoulders, lower back and knees are shown in **table IV**.

Body Mass Index was not significantly associated with reported problems (p=0.11). There were 42 individual kitesurfing styles described by 42 individual participants, which are listed in **Appendix 1**.

During the study, five acute injuries, including one shoulder dislocation and four contusions, were recorded. In 20 overuse injuries, it was possible to apply the Orchard

Table IV. Number of person-days for each type of pain related to shoulder, lower back and knee problems (n=2,096).

	Pain	Shoulder n (%)	Low Back n (%)	Knee n (%)
Kitesurfing related	No pain	1,795 (85.6)	1,391 (66.4)	1,461 (69.7)
	Mild pain	189 (9.0)	504 (24.0)	369 (10.9)
	Moderate pain	56 (2.7)	91 (4.3)	84 (17.6)
	Severe pain	7 (0.3)	7 (0.3)	28 (1.3)
Not kitesurfing related	No pain	28 (1.3)	61 (2.9)	35 (1.7)
	Mild pain	21 (1.0)	14 (0.7)	63 (3.0)
	Moderate pain	0 (0)	28 (1.3)	7 (0.3)
	Severe pain	0 (0)	0 (0)	0 (0)

Sports Injury Classification System OSICS10; they included: shoulder muscle strain (4), knee subluxation, biceps tendon lesion, patellar tendinopathy, pain post PCL reconstruction, pain post ACL reconstruction, lumbar pain nor otherwise specified (5), Patellofemoral impingement (2), Piriformis syndrome (2), pain post shoulder surgery, iliotibial band syndrome.

DISCUSSION

Participants in this study were predominantly male, coherently with existing literature (23). The problem occurrence during the survey period was not associated with BMI. Since the p-value for the association between BMI and reporting any problem at all was 0.11, the limiting issue may have been the sample size. Further research may clarify the relationship between BMI and the probability of experiencing problems due to injury.

Articular pain related to the practice of kitesurfing was commonly reported. In particular, knee pain was reported in 30% of person-days, low back pain in 29% and shoulder pain in 12%. Overuse symptoms also affected sport participation in terms of quantity; person-days of reduced participation related to shoulder, lower back and knee problems were 8 %, 3% and 8 % of the total respectively and quality performance was affected related to shoulder, lower back and knee problems in 11%, 22% and 16% of person-days respectively.

Knee injuries, which are reportedly among the most common in acute injuries (9-24), also accounted for the greatest number and most disabling of overuse injuries, both in terms of reduction of training volume and performance quality. Knee overuse injuries may be prevalent due to the primarily isometric nature of effort required in kiteboarding and exacerbated by absorbed vibrations, repetitive microtrauma and overload during landing from jumps, when the legs bend and absorb part of the impact (13,25,26).

In kitesurfing, low back pain may be caused by the stance on the board. This is because the traction of the kite on the waist keeps the lumbar spine in hyperextension, while extreme loads in compression and bending may expose kitesurfers to overuse injuries (13, 16). Vibration might also play an important role. Literature suggests that the daily amount of vibration to which kitesurfers are exposed exceeds the limits suggested by current EU legislation (19, 28).

The strain on shoulders is relevant only during unhooked maneuvers, when the kiter unhooks the kite from the harness, while remaining temporarily attached to the kite by gripping the bar (10). Unhooked freestyle maneuvers, however, are performed at high speed and often lead to severe acute injuries (i.e. shoulder dislocation) rather than to overuse injuries (9). On the contrary, with the kite normally attached to the harness, musculoskeletal demands placed upon the shoulders are limited, and overuse injuries to the shoulder are less likely than to other anatomic regions (13).

To study overuse injuries in sport is difficult in general (21) but may be even more challenging in kitesurfing. As with most action sports, kitesurfing is an intermittent activity, practiced in specific locations, only when the speed and direction of the wind are appropriate. Exercise programs between kitesurfing periods may assist either prevent injuries or reduce their severity (5,24).

LIMITATIONS

In this study, information is based on self-reported data by athletes, and we cannot exclude that normal symptoms related to sport participation, such as delayed-onset muscle soreness, were confused for overuse injuries. Further limitation is the level of detail collected with the adopted focused-on-symptoms method being limited, and in most cases, the underlying diagnosis was not known. The adoption of telephone interviews by medical personnel was an attempt to

partially overcome these limitations, and in some cases, was able to suggest a possible diagnosis.
In addition, this study was limited to the three predefined injury areas of knees, shoulders and lower back, but it is possible that different body parts are commonly affected by overuse injuries, as have been reported in acute injuries (2,8, 18, 27). In this respect, it may be important to investigate, with the same approach, other articulations (for instance the elbow and the ankle) in order to define in which body areas overuse injuries most commonly occur.
Because each question in the survey investigated if an event had occurred during the previous week, and the responses were binary, it is possible that each type of reported injury may have occurred more than once, and the results in this study may underestimate the number of injuries. It is also unknown what day within the previous week an injury occurred. Therefore, assuming a consequence of seven person-days per injury may overestimate the deleterious effect of reported injuries. Furthermore, participants only had the option of reporting a kitesurfing injury or a non-kitesurfing injury in any week, and the instrument assumes participants would prioritise reporting kitesurfing injuries over non-kitesurfing injuries, if both occurred within the same survey period.

CONCLUSIONS

Overuse injuries emerged as an important cause of reduced participation, damaged performance and discomfort in kitesurfing. The method adopted in this study proved to be adequate to capture the burden of overuse injuries, even in an intermittent action sport such as kitesurfing. Knee overuse symptoms and acute injuries are common, as well as lower back symptoms related to overuse. Epidemiological data reported in this paper are important to underpin the creation of specific training programs to prevent injuries and improve comfort and performance in this sport (5).

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (29).

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ORIGINAL ARTICLE

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Injury Prevention in The Sport of Surfing: An Update

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SUMMARY

Background. The aim of this study is to review the literature on surfing injuries, with a focus on severe injuries, big-wave surfing and injury prevention.
Methods. A literature search of the MEDLINE database from 1980 to present via Pubmed and OVID was done using the terms surfing, bodyboarding, bodysurfing, injury and injuries. Relevant books and websites were also referenced regarding recommendations for injury prevention. A total of 46 articles were retrieved, from which 37 were selected.
Results. The injury rate in surfing has been found to be 1.8 significant injuries per 1,000 hours and 3.5 per 1,000 days for recreational surfers and 4.0 per 1,000 days and 6.6 per 1,000 hours for competitive surfers. Lacerations are the most common type of injury accounting for 37-46% of all injuries followed by sprains/strain, contusions, fractures and dislocations. Impacts with surfboards (45 - 66%) and the sea floor are the most common mechanisms of injury. The most catastrophic injuries include drowning and injuries to the head and neck, often caused by impact with the sea floor.
Conclusions. Surfing is relatively safe compared to other extreme sports. Injury rates can likely be mitigated by the modification of surfboard design and the use of protective personal equipment.

KEY WORDS
Surfing, bodyboarding, injury, injury prevention

BACKGROUND

Surfing, first practiced by Polynesians over 800 years ago, is arguably the oldest extreme sport; it is also among the most popular (1). Since being introduced to the United States and Australia by the Hawaiian Olympic swimming champion, Duke Kahanamoku, in the early 20th century, participation in the sport has grown rapidly (1). A professional surfing tour was first established in 1968 and by a 2013 estimate, there were between 26 and 35 million active surfers worldwide (2,3). In addition, the sport is having its Olympic debut in 2020.

Waves can be ridden in a variety of ways: body surfing (no board); bodyboarding (prone on small board); surfing (standing on surfboard); stand-up paddle boarding also known as SUP (standing on surfboard, propelled by paddle); tow-in surfing (towed onto a wave via jet-ski, riding a surfboard); and surf foiling (standing on board equipped with underwater foil).

The types of waves ridden vary in size, shape, bottom composition and water temperature. Since the 1950's, "big wave" surfers have sought to ride ever bigger waves. By the 1960's, surfers were successfully paddling into waves as high as 7-meters. With the assistance of jet-skis, tow-in surfers began tackling 15-meter waves in the mid-1990's and waves approaching 25 meters by the year 2000. The last decade has seen the improvement of man-made wave pools, enabling high-performance wave-riding at inland locations.

Most of the literature regarding wave-riding injuries consists of survey-based studies, hospital-based chart reviews, or case series focused exclusively on surfing, though some include other wave-riding disciplines. The aim of this paper is to review the hazards associated with wave riding with an emphasis on severe surfing injuries and big-wave surfing (waves > 7 meters). Injury prevention strategies will be addressed in detail.

MATERIALS AND METHODS

The author searched the MEDLINE database from 1980 to present via Pubmed and OVID with the terms surfing, bodyboarding, bodysurfing, injury and injuries. Studies were limited to the English language. While most studies were descriptive and retrospective, some were prospective. Relevant books and websites were also referenced regarding recommendations for injury prevention. A total of 46 articles were retrieved, from which 37 were selected as a result of study size, quality, or focus. Preference was given to hospital-based studies.

RESULTS

Incidence of injury and risk factors

In survey-based studies, Lowden found that the rate of "moderate to severe" injuries (resulting in lost days from surfing/work) was 3.5 and 4.0 per 1,000 surfing-days for amateurs and professionals, respectively (4,5). Furness et al. surveyed 1,348 Australian surfers and found a rate of 1.8 "major" injuries (lost days from surfing/work or sought medical care) per 1,000 surfing-*hours* and that 38% of respondents suffered a major injury within the past 12 months (6). In a prospective study of 37 surfing contests, Nathanson reported 6.6 "significant" (lost time from surfing or requiring sutures or hospitalization) injuries per 1,000 hours of competition and 5.7 per 1,000 heats. These injury rates were significantly less than those for American College football (33 per 1000 h) or soccer (18 per 1000 h) in studies using similar methodologies and definitions of injury (7). A post-hoc analysis of that data found a significantly higher injury rate at the 4 contests held at Oahu's Pipeline (32 per 1,000 h), a large tubular wave breaking over a shallow reef. The relative risk of injury in Nathanson's study was increased by 2.4 when surfing in waves greater than head high, and by 2.6 when surfing over a hard (non-sand) sea floor. Another survey-based study found that surfers older than age 40, and those that were self-rated experts, were almost twice as likely to suffer severe injuries as compared to their younger and less proficient counterparts (8). In a review of 2072 patients presenting to emergency departments across the US, being over 60 years old was associated with a higher risk of admission (9).

Types and mechanisms of injury

Numerous studies have examined type and anatomic location of surfing-related injuries and a few have assessed mechanism of injury. Impacts with surfboards are reported as the leading cause of acute injury (45 - 66%), with the majority of those injuries inflicted by the board's fins, nose, and tail (7, 8, 10). An internet-based survey reporting 1237 acute injuries found that 55% were from the surfer's own board, 11% from another surfer's board, 17% from the sea floor, 7% from the force of the wave, and 3% from marine animals. In one large study, lacerations from surfboard fins accounted for 30% of all acute surfing injuries (8) (**figure 1**). The majority of studies have found lacerations to be the most common type of injury (37% - 46%), followed by sprains/strains, contusions, fractures and dislocations (8, 10, 11). Most commonly injured are the head/face region and lower extremity (**table I**). Overuse injuries are predominantly to the shoulder, back, and knee (10, 14). While minor sprains and strains are common, long bone fractures and dislocations cause a lower proportion of surfing injuries (5-16%) than in many land-based sports, but account for a disproportionate number of surfing injuries requiring hospitalization and surgery. In a retrospective study of injuries among professional surfers at a single orthopedic center, the most frequently injured body parts were knee (28%), ankle (22%), and shoulder (19%). Lower extremity injuries primarily affected the back leg (73%). The most common surgery was repair of rotator cuff tears and superior labrum tears caused by overuse (14).

In big-wave surfing, most injuries are the result of being struck by the powerful cascading lip of a wave and by being

Figure 1. Laceration from fins of surfer's board. Credit: Surf-Co Hawaii.

Table I. Title: Hospital-based studies of waveriding-related injuries.

Study	Chang [12]	Taylor [10]	Hay [11]	Klick [9]	Jubbal [13]
Admission Rate	100%	Unknown	10%	3.5%	71%; 49% ICU
Location	Oahu, US	Victoria, Australia	Cornwall, UK	US	San Diego, US
Number of Subjects	47 (21 bodysurfers)	267	212	2072	93 (16 bodyboarders, 14 bodysurfers)
Average Age	~27	75% < 30	27	27	38
Male Gender	Unkown	83%	80%	82%	90%
Injury Type					
Laceration	13%	47%	35%	41%	Unknown
Sprain/Strain	13%	12%	18%	14%	Unknown
Fracture	45%	14%	20%	12%	Unknown
Dislocation	2%	2%	12%	4.5%	Unknown
Contusion	2%	0%	12%	13%	Unknown
Drowning/Submersion	2%	0%	<1%	<1%	Unknown
Intrabdominal Injuries	2%	0%	<1%	<1%	Unknown
Concussion/Intracranial	17%	3%	2%	7%	Unknown
Other/Unknown	4%	21%a	1%b	8%c	Unknown
Body Region					
Head/Face	34%	42%	40%	40%d	69%
Neck	21%	3%	10%	5%d	20%
Back	0%	1%	2%	0%	5%
Thorax	4%	6%	3%	9%	12%
Upper ext	6%	16%	23%	17%	11%
Lower ext	19%	23%	20%	26%	15%
Intraabdominal	2%	0%	1%*	1<%	5%
Other/Unknown	17%	0%	0%	3%	0%
a Includes 4 eye injuries					
b Larygeal fracture, urethral rupture					
c Dental Injuries, nerve damage, myocardial infarction					

forcefully driven underwater (15). Because big waves generally break deep water, striking the sea floor is unusual. Injuries occurring during the World Surfing League's "Big-wave tour" include shoulder dislocations, ruptured tympanic membranes, long bone and rib fractures, and lung barotrauma, resulting in hemoptysis and pneumothorax. A "shaken surfer syndrome" has also been described in which a surfer emerges from a severe wipeout mildly disoriented and ataxic without loss of consciousness (15).

Surfers are also at risk of environmental injuries including hypothermia, bony exostosis of the ear, otitis externa, pterygium, sunburn and skin cancers, and bites and stings from marine animals such as jellyfish, and stingrays.[8,10,16] While rare, shark attacks also present an environmental risk. There are approximately 66 shark bites reported annually worldwide, with a 7% mortality rate, and 55% involve "surface recreationists" such as surfers and bodyboarders (17).

Severe and catastrophic injuries

Catastrophic and fatal injuries are rare but do occur. Among 2072 patients presenting to US emergency departments, only 5% required admission (9). The most common catastrophic injuries requiring hospitalization are cervical spine fractures, spinal cord injuries, complex lacerations to the face often accompanied by facial fractures, closed head injuries, and drownings (9,13). Deep lacerations caused by surfboard fins involving major vessels, viscera, rectum and head are also well described (18,19). Kim et al reported a series of 11 serious eye injuries all caused by the recoil of the surfer's board on its leash, 5 resulting in permanent loss of vision (24). Blunt trauma from surfboards and the sea floor is less common, but has resulted in splenic and liver injuries, rib fractures and pneumothorax (8,9).

An analysis of 93 patients admitted to a Level 1 Trauma center for wave-riding injuries (surfers, bodyboarders, and bodysurfers), found injuries to the spine (51%), head (46%), and face (23%) were most common. Fifty percent of patients required intensive care unit stays, and 28 surgical interventions were performed, 71% of which involved the head or neck (13). Traumatic brain injury occurred in 34%. Chang, et al analyzed seventy-six cervical spine fracture related to wave-force injuries among body surfers, bodyboarders, skim boarders and surfers in Hawaii and found that 96% occurred in hollow, plunging-type waves breaking over a steeply sloped sea floor. Thirteen percent of patients suffered permanent quadriplegia and 59% of patients were discharged with residual neurologic deficits (20). The study concluded that males over 40 with large builds, pre-existing cervical stenosis and degenerative spondylosis, and little surfing experience may be predisposed to spinal cord injury, predominantly from hyperextension. In younger surfers, axial loading and hyperflexion from head-first contact with the sea floor was the main mechanism of injury. Bodysurfers and bodyboarders are at higher risk for these injuries because they ride head-first, often in plunging near-shore waves breaking into shallow water (20,21).

In 2004, a series of non-traumatic thoracic spinal cord injuries occurring to young, healthy, novice surfers was first described by Thompson, which he termed "surfer's myelopathy" (22). These uncommon spinal cord infarcts typically involve a first-time surfer who develops sudden onset low back pain, lower extremity paresthesia, followed by lower extremity weakness and urinary retention. Recovery is variable with some patients developing permanent paresis and bladder dysfunction. The pathophysiology is thought to involve ischemic injury to the spinal cord, caused by kinking or vasospasm of the artery of Adamkiewicz, related to prolonged hyperextension of the back (23).

Fatalities

The fatality rate in surfing is unknown. According to data from the Hawaii Department of Health, among 538 ocean drowning deaths in that state from 2005 – 14, 7% were surfers or bodyboarders (25) In an epidemiological study of 2072 surfing injuries presenting to emergency departments across the US, there was only 1 fatality (9).

The highest number of fatalities are due to large, powerful, tubular waves which break on to shallow water such as Pipeline, Hawaii (14 deaths since 1960), Teahupo'o, Tahiti (5 deaths) and "The Wedge", California (26). Most of these deaths occur when a surfer goes "over the falls" and hits their head on the sea floor, with resultant loss of consciousness or spinal cord injury. At Jaws (Maui) and Nazare (Portugal), among the most famous big-wave breaks in the world, there have never been any fatalities, and at Maverick's (California) there have been only two (26).

In a review of 95 surfing fatalities occurring from 1982 to 2011 found on the Lexis/Nexis database, drowning was stated to be the cause of death in 63 cases. Factors contributing to these drownings were concussions (11), leash entanglement (4), and seizures (4). Shark attacks were responsible for 12 deaths, lightning strikes for 8 and lacerations from surfboard fins for 2 others (27).

DISCUSSION

The overall incidence of injury in surfing is lower than that of most extreme sports, and in most conditions, compares favorably to many traditional field sports such as football and rugby. Unlike many other sports where there are collisions with hard surfaces or other athletes, water provides a forgiving surface on which to fall. Most surfing injuries occur when a surfer collides with a surfboard or the sea floor, and those risks can likely be mitigated by modifications in surfboard design and the use of personal protective equipment (see below).

The most dangerous waves appear to be those that break over a steeply inclined sea floor, creating powerful, tube-shaped, plunging waves that begin to crest in deeper water, but whose lips land in shallow water. These waves are highly sought after by surfers seeking exciting "tube" rides under a wave's curl. Expert surfers learn how to avoid injury from the sea floor in these conditions by successfully managing to negotiate the takeoff, and by penetrating through the wave during a wipeout, avoiding going "over the falls" and being thrown forcefully onto the sea floor. However, even experts are seriously injured, and on very rare occasions, killed in these conditions. The majority of these fatalities are due to drowning, often precipitated by head and spine injuries.

Since the beginnings of big-wave surfing in the 1950's, fewer than 15 accomplished big-wave surfers have died surfing, far fewer than most other extreme sports (28). By comparison, during that period, over 300 mountain climbers have died on mount Everest alone (29). There are numerous reasons for the surprisingly low number fatalities. Truly big surf only breaks a few times a year at any given location, limiting exposure time. Because of their intimidating nature, few people choose to ride these waves, and those that do are extremely experienced surfers. Furthermore, due to a number of near-drowning episodes among the sport's elite, a culture of safety has evolved. The vast majority of big-wave surfers now wear flotation devices and most have a jet-ski driver available to pull them out of harm's way (30). Since 2011, the Big Wave Risk Assessment Group in Hawaii and others in Europe have organized courses on big-wave risk assessment, jet-ski rescue skills, breath holding, first-aid, and CPR. While some fear that the use of jet-skis and floatation devices may create a false sense of security among less experienced surfers, the number of fatal accidents does not appear to be increasing despite a larger number of participants (31).

Injury prevention

Surfboard

A number of alterations to surfboard design have been proposed to decrease the risk of surfboard-related injuries:

- fins should be designed to break-away with significant impact at their connection point to the surfboard. Fins should have rubberized edges (commercially available) or they should have trailing edges which are at least 2mm wide. The tips of fins should be rounded (4,32);

- noses and tails or boards should be rounded to a "Dolphin Nose" shape with a radius of at least 37 mm as recommended by the Surfrider Foundation Australia. Expert surfers agree that this would result in no change in board performance. Shock-absorbing materials applied to the boards tail and nose are also likely to mitigate board-related injuries (33);
- surfboard leashes are recommended. Leashes keep the surfboard in close proximity to the surfer and the board serves as a flotation device should the surfer become injured or fatigued. They should be designed to minimize recoil, so the board is less likely to snap back at its rider. Leashes should have a quick-release at the surfer's ankle which can be deployed should the leash snag on the sea floor. In big waves, an extra-thick and longer leash should be used (32);
- beginners should use boards made entirely of shock-absorbing material equipped with flexible fins, as they frequently get hit by their own board.

Personal protective gear

Head and facial injuries account for a substantial proportion of surfing injuries, and head injuries resulting in loss of consciousness in the water can be fatal (**table I**). Helmets have been shown to lower the risk of skull fractures and lacerations in other sports and protect against tympanic membrane rupture, however their role in reducing concussions is less clear. Most authorities recommend the use of surf-specific helmets when surfing in large hollow waves over shallow reefs, in strong-offshore winds (boards can become air-borne after a wipeout) when surfing alone, or in very crowded conditions (32). Taylor found that low adoption rates are due to concerns that a helmet may make ducking through oncoming waves more difficult, adversely affect hearing and balance, and may be uncomfortable or unfashionable (34).

Temperature-appropriate wetsuits should be worn, as they not only help to prevent hypothermia, but also provide some buoyancy and protection from UV radiation, abrasions, and jellyfish stings. Surfers are at high risk of developing various forms of skin cancer due to high levels of exposure to UV radiation, and melanoma is likely a leading cause of surfing-related fatalities (35). Avoiding direct sun exposure between 10am and 2pm, wearing sun-protective clothing, and applying sunscreen are the most effective strategies in reducing the risk of sunburn, melanoma and squamous cell carcinoma (36 Burnett). Zink oxide based, broad-spectrum, SPF > 30, 80-minute water-resistant sunscreen should be applied to face, lips, and all other uncovered skin and reapplied every 80-120 minutes. For long surfing sessions, a small tube of sunscreen can be tucked under the wetsuit to facilitate re-application. UV-protective clothing is superior to sunscreen, and in tropical conditions, a long-sleeved rash-guard with a hood or hat should be worn to block UV radiation.

Big-wave surfing

Big-wave surfing (waves >7 m) can be accomplished in relative safety, given the proper experience, physical conditioning, training and equipment. The following recommendations are made based on expert opinion and fatality data.

Jet-skis equipped with an affixed floating sled are excellent surf-rescue tools and have significantly improved the safety of big-wave surfing (**figure 2**). To date, no one has died while tow-in surfing, though there have been a number of non-fatal drownings requiring resuscitation (31). It is essential that jet-ski drivers practice surf-zone pick-up skills with their surfing partners and are trained in first-aid and cardio-pulmonary resuscitation. Water-safety teams at big-wave surfing contests divide a surf break into zones (e.g. outside, impact zone, inside), with 2 skis assigned to each zone. If a driver misses his/her pick-up, a backup is ready. They also use on-shore spotters who can communicate the location of fallen surfers via radio to jet-ski drivers, in order to facilitate rapid pick-up in what is often a dynamic and chaotic environment (15). This strategy serves as good safety model during non-contest days where many surfers have their own jet-ski driver, and some go without. Prior to every big-wave session, an evacuation plan should be in place with a designated ambulance and/or helicopter-accessible evacuation site that can be easily reached from the water.

In big surf, a flotation vest should be worn. Since their implementation, no big-wave surfer has ever died wearing one (28). They help the surfer surface more rapidly in extremely turbulent, highly aerated white-water after a wipeout. They also keep an unconscious victim at the surface where they can be more easily spotted by rescuers. Foam vests provide impact resistance, are not prone to failure and work even if the surfer is unconscious but make diving under oncoming waves more difficult. CO2 – inflatable vests must be triggered by the surfer, but are less bulky, provide greater buoyancy and when uninflated, allow the surfer to more easily dive under approaching waves.

Breath holding is of vital importance to big-wave surfers, as the risk of drowning is always of concern. On very rare occasions, surfers are held underwater by two consecutive waves before surfacing and may need to hold their breath for as long as 40 seconds - this may be extremely challenging following a period of strenuous paddling. Breath-hold training can significantly improve static and dynamic apnea times, which may be life-saving. Training involves mental and physical relaxation to decrease oxygen demand, as well as learning techniques to suppress the urge to breath when experiencing hypercarbia. Anaerobic physical conditioning using high-intensity interval training also aids in breath-holding capacity (37 Fitz-Clark). All in-water apnea training should be done under strict, arms-reach supervision, and hyperventilation prior to a breath-hold should be avoided as shallow water-blackout due to hypoxia can be fatal.

Wipe out techniques

Like riding waves, wiping out is a skill. Surfers have some control over how they fall and the actions they take can minimize their risk of injury.

Just prior to falling, surfers should take in a deep breath, attempt to fall seaward (behind) of their board, and place arms overhead to protect their head and neck. Once submerged, the surfer should stay calm, and avoid attempts to surface until turbulence subsides, so as not to deplete oxygen reserves. Arms should remain over-head until the surfer has surfaced and located their board. In shallow water, the surfer should land flat to maximize the cushioning effect of the water and avoid hitting the sea floor. Wipeouts while tube-riding are the most hazardous, and the objective is to dive cleanly through wave's base, avoiding the lip and the shallows (32 SS2).

In big waves, surfers should always avoid overexertion, by always being prepared for a long underwater hold-down. If "caught inside" of a large breaking wave, the surfer should make all efforts to avoid getting hit by the wave's powerful lip. For waves about to break, it is best to abandon the board (making sure no one is behind) and attempt to swim through the wave's base (**figure 3**). For waves which have already broken, it is safest to dive deeply (3m) to avoid the most severe turbulence (28 Renneker).

Future directions

Artificial wave pools and foiling surfboards are novel developments shaping the future of surfing. Uniform waves at predictable intervals in close proximity to land can be produced at wave pools, which provide a safe environment for those rehabilitating from injury, those learning to surf, and for competitions. In a wave pool the size and shape of the wave can be controlled, the bottom is uniform, there are no hazardous marine animals, and lifeguards and instructors can be close at hand.

Foiling is revolutionizing watersports such as sailing, kiting and surfing. Underwater, airplane shaped foils create lift at relatively low speeds and allow surfer and board to glide above the water's surface, minimizing water resistance. Foiling allows for long, smooth, fast rides in bumpy, mushy, on-shore conditions that would otherwise be considered mediocre for surfing. Skilled surfers can even pump themselves seaward, eliminating the need to paddle out, or glide down open-ocean swells on a SUP. However, the large, multi-tipped foil is capable of inflicting severe lacerations to its rider and others. Therefore, participants should wear a helmet, use a long leash and should consider wearing an impact vest. Surf-foiling is safest in un-crowded, crumbling waves breaking in deeper water. Foils should be designed with rounded wing-tips and dull trailing edges to minimize risk of lacerations and penetrating trauma.

CONCLUSIONS

Surfing appears to be relatively safe when compared to other extreme sports. Risk of injury is increased when surfing in larger waves, over a hard (as compared to sandy) bottom, and with advancing age. Most injuries occur when a surfer

Figure 2. Jet-ski and Rescue sled
Credit: Andrew Nathanson.

Figure 3. Surfer has abandoned board and is swimming through base of wave at Maverick's. Credit: Doug Acton.

collides with his/her own board, with the sea floor, or from the hydraulic force of a breaking wave. Catastrophic and fatal injuries are uncommon, but include head and cervical spine injuries, as well as drowning. Risks of injury can likely be mitigated by slight modifications to the surfboard, as well as use of person-protective gear. In very large surf, floatation personal devices and coordination with a jet-ski driver are recommended. Man-made wave pools may provide a safe environment for training, those rehabilitating from injury, and surfing competitions. The adoption of surf foiling presents a new set of risks to the surfer and others from the large, sharp underwater foil.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (38).

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Injuries in Mountain Biking and Implications for Care

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SUMMARY

Introduction. Mountain biking is a popular recreational activity that has a significant potential for injury.

Methods. This review paper integrates research studies and expert opinion. It examines the various types of mountain biking, associated patterns of injury, trends in the sport, impact on medical services, and expanded roles for health professionals in promoting preventive care and counseling on safe riding practices.

Results. Multiple studies on the frequency of mountain biking injuries suggests that findings may not be reflective of actual injury rates due to under-reporting, as well as inconsistencies in how injuries and injury severity are defined. Given these limitations, it appears that injury rates in mountain biking are on the high end of outdoor sports and that riding downhill is where most serious injuries occur.

Injuries occur most frequently to the upper and lower extremities, with fractures trending towards the upper extremities. Traumatic head injuries and cervical spine injuries are among the most severe injuries, and mountain biking accounts for a significant portion of activity related TBI and spinal injuries. The emergence of e-bikes contributes is attracting older riders to the sport, with potential consequences for increased injury.

Conclusions. The health care community can help in reducing injuries through avenues such as counseling patients and community members about safe riding practices, discussing appropriate gear, working with mountain bike parks to design safer trails and consulting with bicycle manufacturers to design safer bikes.

KEY WORDS

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

INTRODUCTION

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

METHODS

The authors conducted a systematic review to examine the existing scholarly literature on mountain biking injuries. A search of two databases-- PubMed and Engineering Village (Elsevier)--was carried out by a medical librarian, covering the span from database inception to October, 2019. This review served to frame the dimensions of the literature and to gain insight into new directions for research on this topic. Search strategies and retrieval results are as follows: PUBMED: (((mountain) AND (bike OR bikes OR biking))) AND (injury OR injuries OR injury OR injured) 131 articles. ENGINEERING VILLAGE: "mountain biking" and (technology or technologies or safety) 29 articles. The 160 articles were reviewed by the authors for relevance to the topic, study type, and levels of evidence. Of particular interest were articles focusing on injury patterns, technological innovations, and risk reduction. Exclusion criteria included non-English articles, articles that did not specifically concentrate on mountain biking as a recreational or sport activity and articles that did not present data analysis. Ultimately, 55 articles were identified as meaningful to the topic. A thematic analysis of the 55 articles found clustering in four areas: description of injury rates by type and demographic (33); injury case reports (6); review articles (6); and discussions on technology and safety (10).

DEMOGRAPHICS

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

BIKING DISCIPLINES

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

RESEARCH ON INJURY PATTERNS

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

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

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

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

Table I. Literature review summary.

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

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

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

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

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

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

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

Table II. Disciplines of Mountain Biking

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

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

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

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

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

IMPACT OF NEW TECHNOLOGIES

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

E-BIKES

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

WHEEL MODIFICATIONS

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

Table III. Injuries

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

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

FRAME INNOVATIONS

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

PROTECTIVE GEAR

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

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

DISCUSSION

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

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

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

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

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

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

SUMMARY

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

CONFLICT OF INTERESTS

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

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ORIGINAL ARTICLE

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Rodeo Injuries: The Role of Safety Equipment

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SUMMARY

Background. Rodeo is an inherently dangerous competition and the equipment utilized to reduce the risk of injury is not well defined in the existing literature.
Methods. A systematic review of the literature published between 1990 and 2018 was conducted and combined with personal and anecdotal reports to review and assess the role that protective equipment plays in mitigating rodeo-related injuries.
Results. Studies that reported the use of protective equipment noted that helmets and protective vests prevented minor and severe trauma, though did not comprehensively limit fatal events. There was limited literature describing the usefulness of other supportive equipment used for injuries to the extremities and the neck. In studies surveying competitors, many athletes reported underuse of protective equipment due to perceived image and uncertain effectiveness.
Conclusions. Further investigation is required to quantify the impact of protective equipment as it pertains to the incidence of injury in the rodeo population.

KEY WORDS

Rodeo; injury; safety equipment; protective equipment; sports; trauma.

INTRODUCTION

The modern rodeo originated in the United States in the late 1800's with roots stemming from Spanish ranchers and the expansion of the American West (1). In 1929, rodeo was formally organized through the Rodeo Association of America, which led to the rapid expansion in popularity as a spectator sport with promising financial incentives for competitors (1,2). Today, rodeo is a popular competition around the world with the strongest following in the United States, Canada, Brazil, and Australia.

The events that comprise a rodeo have varied over time, but the most common events today are well-established and can be classified into two categories: timed events and roughstock events. The timed events include barrel racing, tie-down roping, steer wrestling, and team roping. All these events involve athletes on horseback attempting to complete a task as quickly as possible. On the other side of the arena, the roughstock events are comprised of saddle bronc riding, bareback bronc riding, and bull riding. In these events, athletes attempt to ride a bucking horse or a bull for a minimum of eight seconds, after which the rider and the animal are each scored by two judges.

To meet the demands of spectators for increased entertainment and excitement in rodeo performances, animals and athletes are becoming better trained and increasingly specialized. The animals have been bred and raised to perform the necessary behaviors required in their respective rodeo events (**figure 1**). The most elite human competitors are now truly professional athletes with full-time focuses on competition and livelihoods relying on success throughout a yearlong season, culminating with lucrative world championships (2,3). There is no doubt that today's rodeo competitions feature some of the strongest and most athletic animals and humans of all time (**figure 2**) (4). The increasingly fast-paced events that either join a rider and an animal together, or pit them against one another, induce an environment prime for human injury. With the growing recognition of injury patterns in sports and the need for athletes to remain healthy throughout the year, safety equipment has been gradually developed over the past 30 years with a progressive adoption by competitors.

For much of rodeo history, protective equipment was largely unused. Gloves, chaps, and cowboy boots were used out of necessity for ranchers and cowboys when working with livestock, and their use was carried over to rodeo events that simulated these activities. This equipment minimizes minor injuries and their design has remained largely unchanged over the years. It was not until July 1989 when World Champion Bull Rider Lane Frost was fatally injured at Cheyenne Frontier Days after being gored by a bull that the need for more substantial protective equipment came into focus. Four years later, in 1993, the first protective vest for bull riding debuted, modeled after a jockey vest used in horse racing (5). Slowly, the protective vest has gained popularity in bull riding and began to cross over into the other roughstock events including bareback and saddle bronc riding. Along with the protective vest in roughstock events came the use of protective helmets; again, adopted from other sports such as hockey and lacrosse (6,7). Currently, protective equipment is steadily gaining traction though the risk of injury still remains high for athletes.

Given the fast-paced and competitive nature of rodeo, and the human interaction with large livestock, there is a high risk and incidence of injuries in competitors. The various types of injuries and the associated mechanisms have been moderately documented in the literature (2,7-9). As noted in existing studies, one of the primary causes of morbidity and mortality in athletes is the result of equipment mishaps and unfavorable interaction with animals (2). In timed events, injury to the joints and hands are most common from dismounting running animals and rope entanglement (2). In roughstock events, the most debilitating injuries are traumatic crush injuries to the head and torso (2). Severe injury also occurs when riders are impacted against a fixed surface, such as being trampled or gored when on the ground or being crushed against the metal fences (2,10). As the modern rodeo has continued to evolve, safety equipment has been further developed and recommended for use, though their implementation has been varied due to the lack of enforcement from governing bodies and lack of compliance from riders.

Figure 1. Bucking bull bred to buck wearing a dummy weight to simulate a rider on its back. Bulls are judged on their bucking ability to select for optimal breeding characteristics. Photo courtesy of Twisted H Bucking Bulls.

The primary governing organizations for adult rodeo competitors are the Professional Rodeo Cowboys Association (PRCA), Professional Bull Riders (PBR), Women's Professional Rodeo Association (WPRA), Senior Pro Rodeo (SPR), and the National Intercollegiate Rodeo Association (NIRA). Each organization regulates the general format of rodeo competitions in a similar manner, but the rules regarding the actions of the individual competitor are less clearly indicated. As a result, rules regarding the use of protective equipment are not widely mandated, and there is limited advisement from governing bodies for competitors to take necessary precautions. Only the NIRA requires a protective vest for all roughstock events with the addition of a helmet with a face mask for bull riding (11). Without mandatory-use guidelines in many competitions, athletes hold to tradition and many do not wear safety gear.

Rodeo athletes report hesitancy to adopt protective equipment due to concerns of losing their cowboy image and the associated machismo along with the limited evidence that the available protective equipment will effectively prevent harm (11,12). There is also a belief and a small amount of anecdotal support that some forms of protective equipment may result in an increased risk of injury. With the uncertainty in the effectiveness of safety equipment, competitors most often adopt protective gear after experiencing an injury, rather than as a preventive measure. Improved pre-market testing of protective equipment is necessary to demonstrate the benefit of its use while meeting the needs of the athletes in their specific events. Future research is needed to understand the function of protective equipment in preventing rodeo injuries.

METHODS

A systematic review of literature was performed through a search of PubMed, Ovid, and Academic Search Premier databases using the key terms “rodeo”, “injuries”, “protective equipment”, and “safety equipment”. Studies from

1990 to 2018 were reviewed. We aim to summarize the common types of injuries sustained in the rodeo population and describe the role that safety equipment plays in minimizing these risks to competitors.

DISCUSSION

Timed Events

Timed events generally pose a lower risk for injury due to the more controlled nature of the events and the lack of large, bucking animals. Though the incidence of injury in these events pales in comparison to the roughstock events, rodeo athletes in timed events still have the possibility of injury that can become debilitating to their lifestyle and continued competition.

Barrel Racing

Barrel racing is typically a female-only event in which a rider on horseback navigates around three large, metal barrels spread across the arena in a cloverleaf pattern. The risk for serious injury in this event is low, though collisions with barrels and falling from a horse running at full speed can pose a serious, and potentially fatal, threat to athlete safety (2,7,10,13). Injury in barrel racing has been noted to occur between 1.5-1.7 times per 1000 competitor-exposures, which results in 0-3% of all rodeo injuries (2,7,9).

As with most timed events in rodeo, protective equipment is generally not worn in barrel racing. Some athletes wear shin guards, either specifically designed for rodeo or adapted from soccer, to reduce the risk of lower leg injuries when contact is made with the barrel. Additional observations from the authors have been made that barrel racers often use rubber bands to secure their feet into their stirrups (**figure 3**). This reduces the chance that the rider would have their feet slip out of the stirrups and then lose

Figures 2a and 2b. World Champion Bull rider Jess Lockwood performing cross training exercises to improve balance, performance, and conditioning and prevent injury. Photo courtesy of Jess Lockwood.

Figure 3. Barrel racer utilizing rubber bands to secure feet into stirrups. The rubber bands help prevent loss of a stirrup during competition but will break if the rider inadvertently dismounts the horse. Photo courtesy of Jason Stoneback.

their balance in the saddle. It provides enough support to reduce the risk of an accident, while still allowing a critical release if the horse falls or the rider needs to dismount suddenly, so as to not be dragged by the horse. Helmets designed for equestrian riding have not traditionally been worn by competitors in barrel racing, though their use is increasing after being worn by a world champion-level rider at the 2014 National Finals Rodeo (14). Previous studies have noted a limited number of fatalities associated with barrel racing (7). The common mechanism for these unfortunate incidents are reported to have been an unplanned dismount in which the rider collided with another object such as the barrels or the arena fencing (2). In general, though significant injuries are a rarity in barrel racing, protective equipment is underutilized.

Steer Wrestling and Tie-Down Roping

Steer wrestling and tie-down roping are similar events in that riders start on horseback and chase a steer or a calf before dismounting their horse to physically restrain the chased animal. In steer wrestling, also referred to as bulldogging, the rider dismounts from their running horse to land directly with their arms around the steer's neck and shoulders with each hand on a horn. The competitor then wrestles the steer to the ground until it is laying on its side with all four legs facing the same direction. In contrast, during tie-down roping, also known as calf roping, the rider uses a lasso to catch a running calf around the head and then ties the lasso to the horn of their saddle. The rider then dismounts the stationary or slowing horse and ties at least three of the four legs together. The rapid dismounts from a horse and the physical manipulation of the steer or calf in both of these events are the most likely sources of injury.

The risk of fatal injury in both of these events is extremely unlikely and no deaths have been reported as a result. Though morbidity is low, competitors still experience a significant number of injuries with steer wrestling, accounting for a reported 8% of injuries and calf roping accounting for 3-12% of injuries (2). Steer wrestlers most commonly suffer from injuries to the joints as a result of landing on the animal and attempting to bring them to a stop (2,7,9). Upper extremity injuries include subluxations, dislocations, and tendon ruptures, often in the shoulder, elbow, and biceps (2,12,15). Injuries to the lower extremities occur most often at the knee, with anterior cruciate and medial collateral ligaments and meniscus injuries being prevalent (2,12). There have also been reports of dental and maxillofacial injuries occurring after riders make unexpected contact with the horns and head of steers (2,9). Previous literature reports that steer wrestlers experience approximately 52 injuries per 1000 competitor-exposures (2). Tie-down ropers also experience similar shoulder and knee injuries along with common roping injuries such as crush, degloving, and amputations when fingers or their thumb become entangled in the lasso rope (2,9).

In these two events competitors do not typically utilize any prophylactic safety equipment besides their standard wear. Some may wear gloves or a mouth guard, though report of their use is limited. After experiencing a joint injury, some athletes will wear commercial braces supplemented with taping and padding (**figure 4**). The use of facial and dental protection should be considered along with athlete-specific braces.

Figure 4. Five-time World Champion Steer Wrestler Luke Branquinho shows the knee braces he wears after bilateral ligamentous knee reconstructions he has required over the course of his career. Photo courtesy of Luke Branquinho.

Team Roping

Team roping is the only true team event in rodeo and is comprised of two competitors on horseback attempting to catch a running steer by the head and then by the back legs. The first roper, the header, uses a lasso to catch and control the steer's head and then turn the rear legs toward the second roper, the heeler, who then uses a lasso to catch the heels. The ropes on either end of the steer are tightened with both horses facing each other and the event is complete. Ropers in this event are at a low risk for mortality, though there is significant risk for damage to the hands. Other injuries are uncommon with a recent review of rodeo injuries citing that team roping comprised only 1-4% of all injuries (2).

When the roper successfully catches their respective part of the steer, they quickly wrap the trailing end of their rope around the horn of their saddle, called dallying, which is typically covered in a rubber wrapping. The rubber on the saddle horn allows the rope to hold tight and helps prevent "running of the rope" where the rope slides and can inadvertently draw fingers into the dally (**figure 5**). Good rubber condition is a critical piece of safety equipment in this event. In the split second that ropers have to wrap the rope around the saddle horn, the fingers can become entrapped and athletes may experience contusions, sprains, crush injuries, degloving, and traumatic amputations (2,9,12,16). The most common and severely injured digit is the thumb (12,16). Though only 53% of ropers report wearing either a leather or cotton glove on their throwing hand, neither of these measures will practically reduce the risk of acute, traumatic injury to the fingers or hand (9,16). A single product has been marketed to reduce the risk of thumb injury, though its effectiveness and practicality are unclear (17). Ropers must utilize extreme caution and proper technique to remain safe.

Contract Personnel

A group of individuals intrinsic to the rodeo that has gone almost entirely unreported in published literature are the contract personnel. This general term encompasses the pick-up men (a term inclusive of both male and female individuals) and the bullfighters, both of which are support staff for the rodeo in timed and roughstock events. In the timed events, they primarily assist with animal management after the roped or wrestled animals are released. In the roughstock events, contract personnel provide a more direct resource to competitors that puts them at a higher level of risk. The pick-up men assist in the bucking horse events and aid the riders off their horse in a more controlled manner. They then release the flank straps on the horse to stop the bucking action and direct the animal out of the arena. The most dangerous role of any of the contract personnel is the bullfighters during the bull riding event. After a successful or unsuccessful ride, the bullfighters attempt to distract the bull to avoid trampling or goring the rider and then guide the animal back to the return gate.

The pick-up men provide a supportive role to the bucking horse riders to minimize their risk of injury after a ride. At the end of the ride, the pick-up man guides his or her horse alongside the bucking horse and allows the rider to dismount and climb onto the pick-up man and his horse. Sudden movements by the bucking horse or misguided dismounts from the rider can cause injury to the pick-up men. These contract personnel utilize shin guards and padded chaps to limit the injury to the lower leg as they get pinned between their horse and the bucking horse. Besides this simple measure, pick-up men utilize their experience and horsemanship to avoid personal injury.

The bullfighters are one of the most iconic images of the rodeo. Once deemed "rodeo clowns", their role has shifted and they are highly athletic individuals with intuition of a bull's behavior. These contract personnel are on foot surrounding a bull rider and quickly step in front of the bull to distract the animal once a rider dismounts. This distraction often puts the bullfighters as the target for the bull's aggression. Bullfighters are at risk of being trampled, gored, and thrown into fencing, similarly to a downed bull rider. Each bullfighter develops their own unique uniform and accompanying protective equipment. Underneath oversized, flashy clothing, the bullfighters will frequently wear padded hockey shorts, knee braces, and support tape. To increase their agility, the bullfighters forgo the standard

Figure 5a. Rubber around the horn of the saddle prevents the rope from sliding excessively and inadvertently pulling digits into the coils of the rope causing injury. Photo courtesy of Jason Stoneback.

Figure 5b. The header has a secure dally allowing the steer to be turned for the heeler to rope the back legs of the steer. Photo courtesy of Jason Stoneback.

cowboy boots and often opt for cleats intended for American football or soccer. The goal is to minimize their own personal injury while protecting the bull riders.
There is almost no existing literature on the injury rates of contract personnel in rodeo, though it is clear they are at a high risk. A single study reported that bullfighting accounted for 8% of trauma, though it is not often considered an official event (2,18). These individuals have exponentially more exposure incidents with the animals compared to the riders and do not typically utilize all of the available safety equipment. Further development is necessary to create equipment that can better protect the contract personnel who perform a critical role throughout the course of a rodeo.

Roughstock Events

Roughstock events are inherently the most dangerous events in rodeo and are the most common cause of injury, with 75-87% of all injured rodeo athletes participating in one of these events (2,7,9,11,19-21). The stark contrast in size between the rider and a relatively unpredictable animal warrants a high potential for unidirectional damage aimed at the athlete. The high velocity movements combined with rapid, multi-directional accelerations create forces that are highly likely to acutely injure athletes or cause long-term musculoskeletal damage. Protective equipment has been primarily developed for, and subsequently utilized in, roughstock events, though their effectiveness is still debated and is not used by all athletes.

Saddle Bronc

Saddle bronc riding is generally considered the least dangerous of the roughstock events as the riders have improved contact points and better control of the bucking horse. There are still reports of serious injury in this event and riders utilize a mix of equipment to minimize risk of injury.
The major injuries in saddle bronc riding are those found in all roughstock events; riders may develop neck and back injuries from the fast, repetitive bucking of the horse and then once dismounted, the riders may get stepped on or kicked. Unique to saddle bronc riders is the occurrence of damage to the surface of the medial malleolus and anterior tibia. As the rider sets their feet forward to spur the horse's shoulders, the anterior tibia repetitively makes contact with the stirrups of the saddle, often causing bruising and/or lacerations to the anterior lower leg. As the rider spurs the animal, the medial aspect of the lower leg often comes into contact with the cantle (posterior seat) of the saddle, causing repetitive trauma to the medial malleolus. This can cause fractures and heterotopic ossification of the medial malleolus.
The saddle bronc athletes utilize a variety of protective equipment to combat the possible injuries during their ride. As the advent of the protective vest became popular in bull riding, it gained traction in bucking horse events. The protective concept is the same and the goal is to provide protection during and after dismounting the horse, primarily if the rider is thrown backwards and is kicked as the horse bucks behind itself or the rider is inadvertently stepped on by the horse. In addition, some riders may wear shin guards under their jeans to prevent stirrup injury and medial malleolus pads in their boots to prevent cantle injury. Leather chaps can have sewn-in padding to protect against bruising of the inner thighs from the saddle swells as well. Finally, saddle bronc riders wear cowboy boots with a riding heel. A riding heel is an elongated base on the boot that allows the cowboy to absorb the impact of the bronc landing on its front feet while preventing the rider's foot from slipping through the stirrup and causing the rider to become stuck in the stirrup. With this moderate level of protection, many riders will still be left bruised or lacerated from frequent, high energy impacts. In contrast to bull riding, helmets are almost entirely non-existent in saddle bronc and the relative number of head injuries is low.
Saddle bronc riders compete in what is generally considered the least dangerous roughstock event. With a more complex rigging scheme and a saddle to provide some level of support, athletes in this event are able to mitigate the incidence of injury. Due to the extra equipment, saddle bronc riders are at a unique risk of injury to the lower extremity. Further education and understanding is necessary to inform competitors on the prognosis of sustaining a head injury and need to utilize a helmet in this event.

Bareback Bronc

Bareback bronc riding poses a higher risk of injury between the two bucking horse events. With only a suitcase-style handle to maintain contact with the horse, riders experience a tremendous amount of energy transfer through a single hand and arm and are at the risk of unplanned dismounts that can lead to acute injury. Additionally, given the nature of the contact point to the horse, riders are less able to hold themselves in an upright position and repeatedly and violently swing onto the hips of the horse as it bucks, potentially leading to head and neck injury (7).
The injuries found in bareback bronc riding are both unique to this event and common to other roughstock events. With the fast, repetitive bucking motion of the horse and limited body control from the riders, the athletes frequently experience whiplash injuries to the head and neck, similar to those found in automobile accidents (12). Additionally, with the small point of contact to the horse, riders experience torquing and hyperextension injuries to the wrist, elbow, and shoulder with regular frequency (**figure 6**). In addition, as

Figure 6. Bareback bronc rider during competition. Photo courtesy Scotty NeSmith.

with all roughstock events, riders are at the risk of getting kicked or trampled during an unexpected dismount.

Bareback bronc riders are at a high risk of acute injuries during their ride. To reduce the risk of injuries to the head and neck, nearly all riders will utilize a neck support that is either separate or built-in to the protective vest that is worn. This can reduce the hyperextension of the neck and avoid contact between the riders' heads and the back of the horse. Some riders may also utilize mouth guards to avoid dental injuries during this repetitive head trauma. In addition, to protect from hyperextension to the arm holding the rigging, riders may prophylactically use a commercial elbow brace or simple athletic tape for support (**figure 7**). At the shoulder, there is an extreme force pulling the arm in the inferior direction that can lead to subluxation or dislocation. Some riders may use tape or other supportive measures, though this is typically utilized after an injury is sustained. Most riders wear a protective vest to provide a moderate level of protection from the metal flank strap buckles that impact the rider or in the event of a high-energy impact from the horse during dismount. Limited use of protective helmets has been noted.

Riders in bareback bronc events are at a high risk of sudden, whiplash-type injuries. Further investigation is needed to better protect the wrist, elbow, and shoulder from injury during this event. Additionally, further study is required to determine if helmet use would prevent concussion or if helmet use may increase injury rates from the increased weight of the riders head.

Bull Riding

Bull riding has been notoriously deemed, "the most dangerous eight seconds in sports", due to the high incidence of severe injury with 28-50% of all rodeo injuries coming from this event (2,6,8,19). The bull may easily outweigh the rider ten-fold and is prone to aggressive behavior. With only a tightly wrapped rope to secure the rider's hand to the bull, it is easy for the rider to lose control and have serious injury during the ride and during dismount. Furthermore, athletes who successfully ride for the minimum eight seconds are required to dismount to the ground, opposed to a pick-up man in bucking horse events, which can lead to injury. In agreement with general perception, there is strong evidence that bull riding is by far the most dangerous rodeo event overall.

Figure 7. Bareback rider after a ride and dismount in the arena. Note the large neck roll to help prevent hyperextension injury of the neck and prophylactically taped right riding elbow to prevent hyperextension of the elbow during the ride. Photo courtesy of Scotty NeSmith.

Competitors in bull riding can experience injuries similar to those in unrestrained vehicle crashes as well as an entire gamut of orthopedic injuries. Before the ride even begins, riders in the chute are at risk of the bull becoming agitated and bucking, which can lead to lower extremities being pinned against the bucking chutes or the rider getting thrown into, off, or under the bull. Once the ride begins, the only connection to the bull is through a suitcase-style handle and rope held in a single hand. The fast spinning and bucking nature of the bull causes riders to slide laterally while being thrown anteriorly and posteriorly on the bull. Severe head trauma can occur if contact is made with the bull's head or horns, as it has been observed that injuries to the head and neck account for 27% of all bull riding injuries (8). Riders also experience injury to the hand, wrist, elbow, and shoulder of the arm holding the bull rope. Once the ride is over, the riders are at the greatest risk for life-threatening injury. Riders can get "hung up", which is a term that describes an incident in which the rider cannot remove their hand from the rope around the bull. This often results in the rider being dragged by the bull and often falling underneath the animal as it stomps. As the rider dismounts the bull completely, if they land underneath or in the path of the bull, they are at risk of being trampled and crushed by the bull. The aggressive bull is also prone to goring competitors with its horns as they attempt to escape after dismount. Being trampled or gored may lead to traumatic injury to the chest, abdomen, and pelvis which are the leading causes of death in roughstock events (2).

Bull riders are typically the most protected athletes in the rodeo, though they still experience the highest rate of morbidity and mortality with 92.5% of surveyed riders responding that they have experienced an injury in their career (8,11,19). After polarizing deaths to rodeo riders years ago, protective vests and helmets have come in to popularity with reports that 95% of bull riders always wear vests (11). The helmet and vest provide adequate protection during the ride and during dismount if the athletes are kicked, but they often do little to stop the crush injuries that occur if a rider is trampled or gored while on the ground or pinned into the metal fencing (**figure 8**) (2,7). While vests are utilized by nearly all riders, helmet use is split due to the incidence of secondary injuries (7) and the belief that helmets impair riding ability, with only 31% of bull riders reporting to always wear a helmet (7,11). One example of a secondary injury sustained through the use of a helmet that has been noted by the senior author is traumatic ear lacerations and avulsions as a result of the helmet moving during impact. The proposed mechanism for this is that a torsional force occurs when a rider's helmet is violently impacted on a bull's head or horns. The helmet rotates circumferentially on the riders head and the ear is avulsed by the cutouts in the helmet surrounding the ear. Furthermore, inconsistent use of helmets is driven by athlete perception, as it has been noted that 17% of riders report that helmets restrict vision and 14% report they affect their general riding ability (11). Most helmets had been adopted from other contact sports such as hockey and lacrosse, but with the introduction of a rodeo-specific helmet, the Bull Tough Helmet, athlete perception may be altered (22). Most athletes (61%) in this event are also utilizing mouth guards to decrease the incidence of preventable dental injuries (11). Support for the wrist, elbow, and shoulder are often achieved through the use of commercial braces and athlete-specific taping regiments, though the use of this equipment is rarely overseen by a medical professional and is primarily used by riders who have experienced a previous injury.

There is still much to be learned about the effectiveness of protective equipment in bull riding. Further design and development is necessary to create helmets and vests that can better resist acute traumatic injury, while also allowing

Figure 8. Bull rider during competition. Note the use of protective vest and helmet with faceguard. Photo courtesy of Colton Fritzlan.

the rider to maintain their physical function required to ride a bull successfully. Until that time, riders should consider utilizing the available equipment to reduce the risk of other preventable injury.

CONCLUSIONS

Rodeo is an inherently dangerous and injury-prone sport that has a history deeply rooted in cowboy culture. Though sports medicine has continued to evolve in this environment, the attitudes and beliefs of riders and spectators adversely support the use of protective equipment. To complicate this philosophy, the effectiveness of the various forms of safety equipment available is still uncertain. Though it is not definitively proven, the prevailing literature suggests that the use of modern protective equipment can reduce the risk of injury and lead to fewer debilitating or fatal injuries (11).
Additional research, development, and testing is necessary to develop protective equipment that can withstand the unique high energy exposures that rodeo athletes encounter while providing the freedom of movement these athletes need to be successful. There is need for biomechanical research to quantify the forces involved in acute injuries and need for epidemiological studies to establish the role that safety equipment plays in reducing the incidence of injury in rodeo athletes.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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Current Trends in Sport Climbing Injuries after the Inclusion into the Olympic Program. Analysis of 633 Injuries within the years 2017/18

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SUMMARY

Objective. To prospectively evaluate current demographics, distribution and severity of rock climbing-related injuries after the sport's inclusion into the Olympic program and to analyze changes in comparison to two prior study populations.

Methods. In 2017-2018, we performed a single-center injury survey including 436 climbing patients with a total number of 633 independent climbing-related injuries or complaints.

Results. 77.1% of the injuries affected the upper extremities, 17.7% the lower and 5.2% other body regions. Injury severity was overall low (Union Internationale des Associations d'Alpinisme (UIAA) metric scale: 1.8 ± 1 (1-4)). The most frequent injuries were finger pulley injuries (12.3%) and finger tenosynovitis (10.6%). 43.9% of reported injuries were acute and 56.1% were chronic. Bouldering accidents were the leading cause of acute injuries (60.4%). Among shoulder injuries, superior labral lesion tears from anterior to posterior (SLAP) represented the leading diagnosis (29.8%). In comparison to our two prior study populations (1998-2001 and 2009-2012), we found: 1) an overall decrease in upper extremity injuries, 2) an increase of lower extremity injuries, 3) a constant decrease of finger pulley injuries and epicondylitis, 4) a rise of knee injuries and shoulder dislocations, 5) an increase of adolescents finger growth plate injuries.

Conclusions. Severity of climbing injuries is low overall. Distinct trends are noticeable: being that some injury rates rose while others fell, preventative strategies only seem partially effective. Therefore, adjustment of preventive strategies is required.

KEY WORDS

Olympia; bouldering; speed; lead; injury surveillance

INTRODUCTION

Rock climbing experienced a rapid increase in popularity over the last few years and will be presented as a new Olympic discipline during the Olympic Games in Tokyo 2020 (1). With the introduction of modern climbing styles and the inclusion of climbing into the Olympic program, the sport has experienced massive changes in terms of professionalization, public attention, and number of sports enthusiasts. While several studies on injury demographics and severity have been published, recently, several studies reported injury mechanisms and specifications which have been rarely seen in the past-indicating a change in injury demographics, distribution and severity (10-12). Various authors attribute the rise in new climbing injury patterns and change in injury distribution to modern steep and three-dimensional wall architecture, trends in route setting, and the wave of untrained beginners within the sport (1, 2, 12).

Moreover, we recently argued that recent demographic changes in climbing participation have brought up sport specific injury patterns (e.g. knee injuries) that were rarely seen in the past (1, 2). Until today, studies have shown, that overuse injuries in climbing mainly affect the upper extremity, whereas, acute trauma predominantly occurs at the lower extremity (3-8). There are many different subdisciplines in rock climbing (e.g. Bouldering, Alpine-, Speed Climbing); the new trend is to enjoy the easy availability of indoor climbing and bouldering gyms (2). Various studies analyzing injury severity of different climbing subdisciplines have indicated a low injury rate in those two subdisciplines of rock climbing (9).

The assessment of current trends and distributions of injuries can emphasize further preventive strategies and allow a continued assessment of the previous preventive measures.

To evaluate current demographics, distribution, and severity of rock climbing related injuries since its inclusion into the Olympic program, we conducted a clinical follow-up study, allowing direct comparison to two prior study populations (14, 15).

METHODS

From January 1st, 2017 to December 31st, 2018, all patients that presented at our clinic complaining of acute or overuse injuries caused by rock climbing and/or bouldering were assessed (**table I**). The study was approved by the institutional review board and all patients provided informed consent. Athletes were seen and treated in our specialized out-patient sports medicine clinic which is a referral center for climbing related injuries (e.g. German Alpine Club). Diagnoses were made based on clinical investigation and radiological findings by three experienced orthopedic surgeons (MS, CL, VS) in the field of climbing-related injuries. All final diagnoses were reviewed and confirmed by

Table I. Patient injury distribution and grading 2017-2018 compared with two prior studies (14,15).

Patients	2017-2018 (n = 436)	2009-2012 (n = 836)	1998-2001 (n = 604)
Number of injuries	633	911	604
Age, years	30.8 ± 11.2 (8-67)	34.1 ± 11.1 (11–77)	28.3 ± 12.4 (13–52)
Sex (men-women)	299-137	630-206	
Climbing level (UIAA metric)	8.6 ± 1.2 (4.3-12)	8.8 ± 1.2 (5.0–11.3)	8.6 ± 1.1 (5.3–11.0)
Bouldering level (V-scale)	5.7 ± 4.0 (0-15)	-	-
Climbing years	9.7 ± 9.2 (0-47)	13.3 ± 10.1 (0.3–64)	7.3 ± 5.8 (2–35)
Climbing hours/week	9.6 ± 5.8 (0.2-35)	-	-
Height (cm)	175 ± 9.5 (130-197)	-	-
Weight (kg)	67.5 ± 11.7 (28-102)	-	-
Body mass index	21.9 ± 2.4 (15.2-34.9)	-	-
Women	20.6 ± 2.3 (15.9-31.8)	-	-
Men	22.4 ± 2.3 (15.2-34.9)	-	-
Injury distribution			
Upper extremity	488 (77.1)	833 (91.4)	405 (67.1)
Lower extremity	112 (17.7)	58 (6.4)	77 (12.7)
Other	33 (5.2)	20 (2.2)	122 (20.2)
Injury grading	1.8 ± 1 (1-4)		
UIAA 1	131 (20.1)	17 (1.9)	4 (0.6)
UIAA 2	461 (72.1)	881 (96.7)	584 (96.7)
UIAA 3	40 (6.3)	13 (1.4)	9 (1.5)
UIAA 4	1 (0.1)	None	7 (1.2)
UIAA 5-6	None	None	None
Injury type			
Acute	278 (43.9)	380 (41.7)	308 (51)
Overuse injuries	355 (56.1)	531 (58.3)	296 (49)
Cause of acute injury			
Bouldering	168 (60.4)		
Rock climbing	88 (31.7)	"mostly"	
Other	22 (7.9)		

the senior author (VS). Patients with acute injuries initially seen and treated in the emergency department of our 24-hour, level 1 trauma center were later re-examined in the out-patients sports medicine clinic. The clinic is one of three trauma centers of Germany's biggest outdoor sport-climbing and bouldering areas, the Frankenjura. A standard questionnaire, which included questions about medical history, and a physical examination protocol were conducted on all patients. Only patients suffering from pain during or after climbing were included in the study. Injuries caused by rock climbing or bouldering activities were defined as medical conditions forcing the athlete to rest from his/her sport due to pain or dysfunction and the necessity to seek help from a physician. While acute injuries were defined as injuries with a sudden onset during climbing without any prior history of complaints, overuse injuries were defined as chronic injuries without a singular causing event or a specific trauma that had developed during or after climbing. The Union Internationale des Associations d'Alpinisme (UIAA) metric scale was used for evaluation of climbing levels as in two previous studies from our center (years 1998-2001: 604 climbing injuries; and 2009-2012: 911 climbing injuries) (14, 15). Injuries were graded according to the UIAA injury score. The orchard sports injury classification system 10 (OSICS 10) scale was used to categorize the injury distribution following the Union Internationale des Associations d'Alpinisme (UIAA) MedCom recommendation (13, 16).

Microsoft Excel (Microsoft, Redmond, Washington, USA) was used for data collection; statistical analyses were performed using SigmaStat software (Systat Software Inc., San Jose, USA). Values were checked for normality with the Shapiro-Wilk test. To determine the difference between the groups, a t-test or rank-sum test was used depending on normal distribution. P-values < 0.05 were considered as statistically significant.

RESULTS

In 2017 and 2018, 436 patients were treated with 633 independent injuries caused by rock climbing or bouldering (**table I**). Of the 436 patients, 197 patients had two injuries within the study period. Among the 633 injuries, 355 (56.1%) were overuse injuries and 278 (43.9%) were acute injuries. The acute injury mechanism rates were bouldering (60.4%), rock climbing (31.7%) and other (e.g. hangboard training, 7.9%) (**table I**). The upper extremity was affected in 77.1%, the lower extremity in 17.7% and the head, neck and trunk in 5.2% of all cases. For detailed information on injury distribution, see **tables I-III** and **figure 1**. The mean climbing level (UIAA 8.6 ± 1.2 (4.3-12)) was constant as compared to the two prior study populations (1998-2001: mean UIAA grade 8.6; 2009-2012: mean UIAA grade 8.8) (**table I**). Localizations of injuries following the OSICS 10 score are presented in **table III** (13). **Table IV** provides a comparison of the injury distribution (ten most frequent injuries), as previously published (**table IV, figure 2**). Finger injuries represented 41.2% of all injuries and shoulder injuries accounted for 20.2%. Hand injuries (7.7%), forearm/elbow pathologies (7.7%) and lower leg/foot injuries (10.6%) were diagnosed less often (**table II, figure 1**). Finger pulley injuries represented 12.3% of all injuries and accounted for 29.9% of all finger injuries. This diagnosis was the most frequently seen injury in the study group, followed by finger tenosynovitis (10.6%), and finger joint capsulitis (7.7%) (Table 4). Overall, 17 different diagnoses of finger injuries were present (**table V, figure 3**). Among shoulder injuries, SLAP tears were found most frequently (29.8%), followed by subacromial impingement syndromes (27.4%) and dislocations/Bankart lesions (17.7%) (**table VI**), The average UIAA injury score was 1.8 ± 1 (1-4). None of the athletes suffered a UIAA grade 5 injury and none of them died (UIAA 6) (Table 1). Climbing level (UIAA level, p=0.006) and climbing experience (climbing years, p=0.029) were both significantly higher in men than in women. The difference in climbing levels was lower than in prior studies; mean female UIAA level was 8.33 and mean male UIAA level was 8.73, respectively. Climbing levels showed a wider range than in the past, meaning that there was an increased number of both beginner athletes and world-class athletes within the study population (**table I**).

In comparison with the two prior study periods, the main findings were: the upper extremity was less affected in the presented study population, whereas, lower extremity injuries were diagnosed more frequently (14, 15) (**tables I-III**). Finger pulley injuries consistently decreased from 20.2% (1998-2001) and 15.4% (2009-2012) to 12.3% in the current analysis (**table IV**). Similar findings were seen for epicondylitis, which currently represented only 3.3 % (1998-2001: 8.4%, 2009-2012: 5.5%). Knee injuries, wrist strains and epiphyseal fractures of the finger were found to be among the ten most frequently diagnosed injuries, whereas, they were not seen frequently within the two prior studies (**table IV**). Epiphyseal fractures, which were seen in 0.8% of all cases between 1998-2001 and 3.4% from 2009-2012, were present in 7.3% of all finger injuries within our athletes (**tables IV and V**). Among the shoulder pathologies, we found a rise of shoulder dislocations (2009-2012: 10.2%, 2017-2018: 17.7%) and acromioclavicular joint injuries (2009-2012: 1.9%, 2017-2018: 9.7%) (**table VI**).

Table II. Injury distribution according to body area as presented previously (data of trunk, spine and pelvis merged). Values are n (%).

Body area	2017-2018 (n = 633)	2009-2012 (n = 911)	1998-2001 (n=604)
Finger	261 (41.2)	474 (52)	247 (41)
Shoulder	128 (20.2)	157 (17.2)	30 (5)
Hand	49 (7.7)	119 (13.1)	47 (7.8)
Forearm and elbow	49 (7.7)	83 (9.1)	81 (13.4)
Lower leg/foot	67 (10.6)	35 (3.8)	55 (9.1)
Knee	45 (7.1)	19 (2.1)	22 (3.6)
Trunk, spine, pelvis	34 (5.4)	21 (2.3)	43 (7.1)
Other	-	3 (0.3)	-

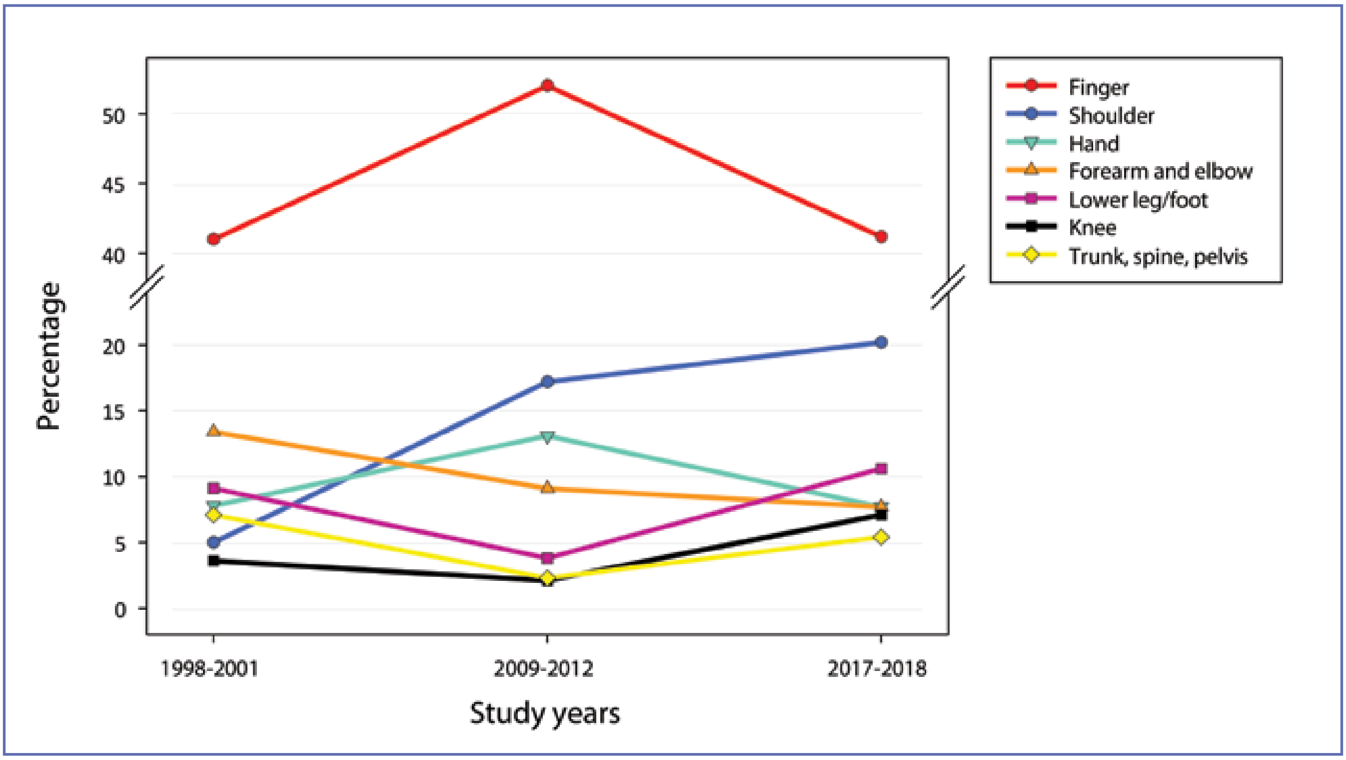

Figure 1. Injury distribution according to body area compared with two prior studies.

DISCUSSION

This study focuses on current trends and changes in rock climbing related injuries since its inclusion into the Olympic program for Tokyo 2020 (1). Two prior studies have been conducted with the same methods, allowing a direct comparison and interpretation of data (14, 15). The gap between the two first studies was 10 years, and 7 years have passed since the last (2009-2012). However, the world-wide rise of bouldering within the last 7-8 years, and the inclusion into the Olympics, has changed the sport rapidly (12, 17). On one hand, more and more athletes around the world are enthusiastic about rock climbing and bouldering, and on the other, the sport also professionalises rapidly (1). Our study population nicely represents both the changes, as more beginners and world-class athletes were among the patients than in our prior studies. Mean climbing levels were

Table III. Anatomical sites according to Orchard Sports Injury Classification System 10 (OSICS). Values are n (%). (Data 1998-2001 n.A.).

Main grouping	Category	OSICS Designation	2017-2018 (n = 633)	2009-2012 (n = 911)
Head and neck	Head/face	H	1 (0.2)	0 (0)
	Neck/cervical spine	N	3 (0.5)	4 (0.4)
Upper limbs	Shoulder/clavicle	S	115 (18.2)	157 (17.2)
	Upper arm	U	14 (2.2)	0 (0)
	Elbow	E	39 (6.2)	70 (7.7)
	Forearm	R	10 (1.6)	12 (1.3)
	Wrist	W	32 (5.1)	69 (7.6)
	Hand/finger/thumb	P	276 (43.6)	528 (57.1)
Trunk	Chest (sternum/ribs)	C	2 (0.3)	0 (0)
	Thoracic spine	D	5 (0.8)	0 (0)
	Trunk, abdomen	O	2 (0.3)	0 (0)
	Lumbar spine	B	9 (1.4)	11 (1.2)
	Pelvis and buttock	L	7 (1.1)	2 (0.2)
Lower limbs	Hip/groin	G	5 (0.8)	4 (0.4)
	Thigh	T	6 (0.9)	0 (0)
	Knee	K	45 (7.1)	19 (2.1)
	Lower leg	Q	7 (1.1)	3 (0.3)
	Ankle	A	39 (6.2)	12 (1.3)
	Foot/toe	F	15 (2.4)	20 (2.2)
Location unspecified		X	1 (0.2)	0 (0)

Table IV. Distribution of diagnoses (ten most frequent injuries).

Injuries 2017-2018 (n = 633)	n	%	Injuries 2009-2012 (n = 911)	n	%	Injuries 1998-2001 (n = 604)	n	%
Pulley injury (finger)	78	12,3	Pulley injury (finger)	140	15,4	Pulley injury (finger)	122	20,2
Tenosynovitis (finger)	67	10,6	Capsulitis (finger)	87	9,5	Epicondylitis	51	8,4
Capsulitis (finger)	49	7,7	Tenosynovitis (finger)	80	8,8	Tenosynovitis (finger)	42	7,0
Knee injury	45	7,1	SLAP tear	51	5,6	Strain finger joint capsule	37	6,1
SLAP tear (shoulder)	37	5,8	Epicondylitis	50	5,5	Skin abrasions	34	5,6
Impingement (shoulder)	34	5,4	Impingement (shoulder)	40	4,4	Back problems	24	4,0
Wrist strain	22	3,5	Strain finger flexor tendon	36	4,0	Knee injuries	14	2,3
Epicondylitis	21	3,3	Dupuytren disease	30	3,3	Fractures	14	2,3
Growth plate injuries (finger)	19	3,0	Strain finger joint capsule	25	2,7	Capsulitis (finger)	13	2,2
Spinal injuries	18	2,8	Ganglion finger flexor tendon	19	2,1	Ganglion finger flexor tendon	11	1,8

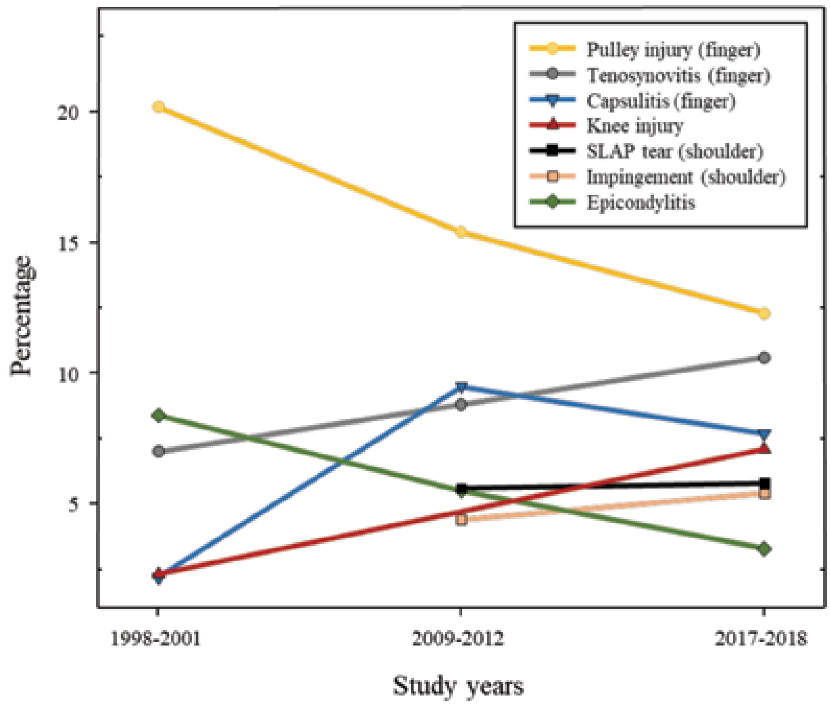

Figure 2. Development of most frequent injuries over the three different survey periods.

Table V. Most frequent finger injuries 2017-2018 (n=261), 2009–2012 (n=474) and 1998–2001 (247).

Finger injuries 2017-2018 (n=261)	n	%	Finger injuries 2009-2012 (n=474)	n	%	Finger injuries 1998-2001 (n=247)	n	%
Pulley injury	78	29.9	Pulley injury	140	29.5	Pulley injury	122	49.4
Tenosynovitis flexor tendon	67	25.7	Capsulitis	87	18.4	Tenosynovitis	42	17.0
Capsulitis	49	18.8	Tenosynovitis flexor tendon	80	16.9	Strain finger joint capsule	37	15.0
Epiphyseal fracture	19	7.3	Strain flexor tendon	36	7.6	Capsulitis	13	5.3
Lumbrical tear/strain	12	4.6	Strain finger joint capsule	25	5.3	Ganglion	11	4.5
Strain finger joint capsule	10	3.8	Ganglion finger flexor tendon	19	4.0	Strain flexor tendon	7	2.8
Osteoarthritis	5	1.9	Lumbrical shift syndrome	19	4.0	Fracture	7	2.8
Strain flexor tendon	4	1.5	Collateral ligament injury	17	3.6	Osteoarthritis	7	2.8
Ganglion finger flexor tendon	3	1.2	Epiphyseal fracture	16	3.4	Soft tissue injury	5	2.0
Contusion	3	1.2	Osteoarthritis	14	3.0	Tendon rupture	4	1.6
Phlegmonia/cellulitis	2	0.7	Extensor hood syndrome	7	1.5	Collateral ligament injury	3	1.2
Collateral ligament injury	2	0.7	Lumbrical tear/strain	4	0.8	Osseous tear fibrocartilago palmaris	2	0.8
Distorsion thumb	1	0.3	Snap finger	3	0.6	Epiphyseal fracture	2	0.8

Table V. *Continues*

Finger injuries 2017-2018 (n=261)	n	%	Finger injuries 2009-2012 (n=474)	n	%	Finger injuries 1998-2001 (n=247)	n	%
Disruption volar plate	1	0.3	Cartilage injury	2	0.4	Lumbrical tear/strain	2	0.8
Cartilage injury	1	0.3	Flip phenomena	2	0.4	Phlegmonia/cellulitis	1	0.4
Neuropraxia	1	0.3	Broken osteophyte	1	0.2	Finger amputation	1	0.4
PIP joint dislocation	1	0.3	Avulsion fracture	1	0.2	-	-	-
Snap finger	1	0.3	Flexor contraction	1	0.2	-	-	-
Contracture finger flexor tendon	1	0.3	Rupture connexus intertend.	1	0.2	-	-	-
-	-	-	Enchondroma	1	0.2	-	-	-
-	-	-	Contusion	1	0.2	-	-	-
-	-	-	Tendon rupture	1	0.2	-	-	-

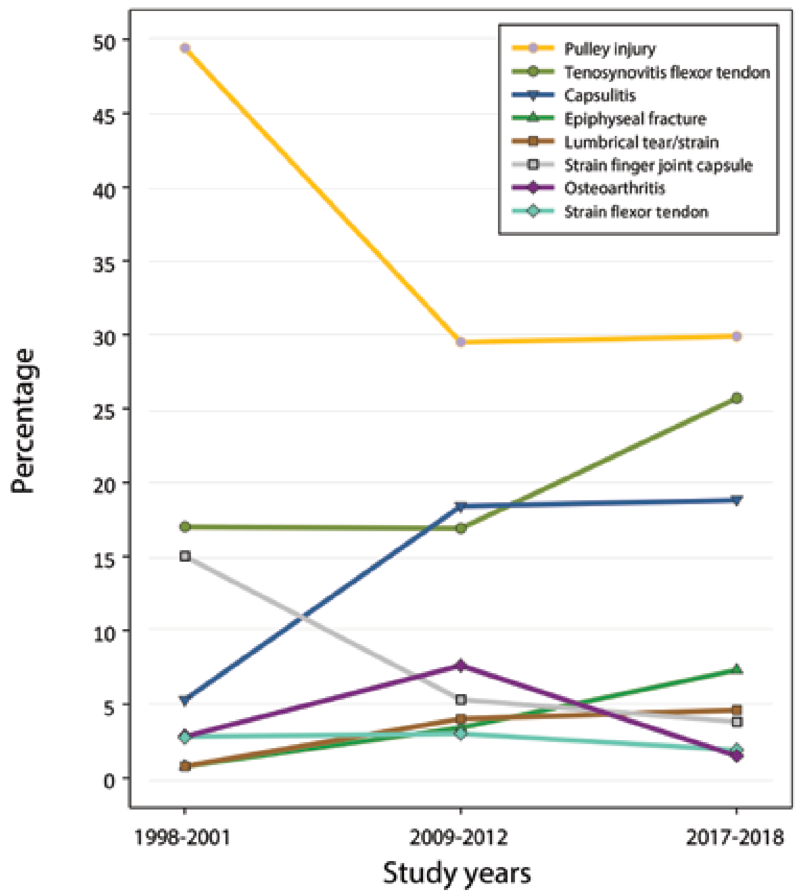

Figure 3. Development of most frequent finger injuries over the three different survey periods.

consistent among our three study periods, but a vast scatter over the entire UIAA climbing level scale currently highlights a wide study population. UIAA level one represents the easiest possible climb and UIAA level 12 the world's hardest climbs. Both are represented in the study group.

While most of our patients predominantly climb within the local climbing areas and gyms, several athletes from other regions sought our advice as a second opinion after injuring themselves climbing in other areas. This is consistent with the two prior studies (14, 15). The fact that the mean difference in climbing levels among genders was lower than other studies might be explained by the higher percentage of beginners within the current analysis. Male athletes, in general, might have a slightly higher climbing performance potential than female, but gender specific differences are seen less in beginners (3, 5, 12, 18-22). Our data does not allow answering the question whether or not men or female are more risk prone. Self-efficacy and sex differences (higher in males) emerged as important predictors of risk in rock climbing in a psychological analysis (23) and Neuhof et al. (2011) (24) found a higher injury rate (number of

Table VIII. Distribution of shoulder injuries.

Shoulder Injuries 2017-2018 (n = 154)	n	%	Shoulder Injuries 2009-2012 (n = 157)	n	%
SLAP	37	29.8	SLAP	51	32.5
Impingement	34	27.4	Impingement	40	25.5
Dislocation. bankart lesion	22	17.7	Shoulder sprain	17	10.8
Shoulder sprain	16	12.9	Dislocation. bankart lesion	16	10.2
Rotator cuff tear	12	9.7	Supraspinatus tendonitis	7	4.5
Acromioclavicular joint injury	12	9.7	Instability (non-bankart)	7	4.5
Tendinosis of long biceps tendon	6	4.8	Tendinosis of long biceps tendon	5	3.2
Instability (non-bankart)	5	4.0	Rupture of long biceps tendon	5	3.2
Pulley injury	5	4.0	Rotator cuff tear	5	3.2
Rupture of long biceps tendon	2	1.6	Acromioclavicular joint injury	3	1.9
Other	2	1.6	Pulley injury	1	0.6
Supraspinatus tendonitis	1	0.8			

injuries divided through 1000 hours of sport participation) for female (0.23) than for male (0.19) climbers (p=0.83). In contrast, Josephsen et al. (25) found no relation of bouldering injuries to gender, years of climbing, body mass index or weight.

While an overall low injury rate has been described for bouldering in the past (4, 25-29), the vast majority of acute injuries in our athletes was found to result from this sub-discipline (30). This fact might be explained by the new wave of beginners that perform indoor bouldering and who were described to be prone to get injured more frequently (2, 31). Considering acutely injured athletes generally seek help at the closest medical facility rather than a facility specialized in climbing injuries (15), it must be assumed that acute injuries in both bouldering and rock climbing are underrepresented in our study. This is especially true in cases of fractures or acute ligament injuries. Injuries that are known to result from ground falls during bouldering, rather than from rope protected climbing, are knee injuries and dislocations of the shoulder (both glenohumeral and acromio-clavicular joints). The percentage of knee injuries increased from 2.3% (1998-2001) to 7.1% (current study group) while glenohumeral shoulder dislocations and acromioclavicular joint injuries increased from 10.2% and 1.9% (2009-2012) to 17.7% and 9.7%, respectively (**tables IV, VI**). There could be a slight sample bias, as the authors specialize in sports medicine upper extremity and knee surgery. However, the findings coincide with other recently published studies (12, 17). In addition, that sample bias already existed in prior studies, and would therefore not influence a comparison to these data.

The introduction of several preventive strategies (e.g. increase in climber's and coach's awareness on warm up strategies, antagonist training and neglect of certain training strategies, such as pull-ups with uniform hand positioning routines or finger taping) have been established to increase awareness and reduce prevalence of various injury types. Ever since, physical complaints such as pulley injuries and epicondylitis ("climbers' elbow") have decreasingly been detected/diagnosed (14, 15). Various associations, such as the British Mountaineering Council (BMC), support and actively promote prevention programs (https://www.thebmc.co.uk/growth-plate-stress-fractures-in-teenage-climbers). Unfortunately, preventive measures have not yet caused a decrease of epiphyseal injuries in adolescent athletes in our current population (15, 32, 33). Since the first study (1998-2001) a sevenfold increase of this injury type has been observed (14, 15) (**table V**). This increase can partially be explained by the rising numbers of adolescent athletes that goes along with the world-wide climbing and bouldering hype. However, a positive finding among the affected athletes was that none of the 19 patients reported having trained on a campus board training tool, which is known to strongly favor the development of epiphyseal injuries of the finger and showed significance for early osteoarthritis in young climbers (15). The numbers, however, are still alarming and need to be further acknowledged by the national and international climbing community. Precautions need to be implemented and early detection needs to be increased. Even if it may seem as previous work on prophylaxis and knowledge transfer may not have influenced this specific epidemiology, we predominantly see these injuries at an earlier, and thus better, treatable stage. Hopefully, increased public awareness will give better treatment options and lead to better outcomes in the future. In this respect, we perform ultrasound scans in young climbers of national, state, and regional teams during our yearly examination (18). During these exams, we evaluate the most vulnerable phase for growth plate fractures, known to be the period just before dorsal closure of the growth plates during their peak growth spurt (34). Climbers and parents are informed about the increased risk and advised to seek immediate consultation in the case of dorsal sided finger pain after climbing that continues for more than one week (35). To avoid epiphyseal stress reactions, load management and recovery must be encouraged, particularly in young athletes which are strongly motivated to incessantly train and climb. It is important to better reach adolescent athletes and their parents, especially those without trainers, to draw attention to the dangers and symptoms growth plate injuries, and to inform them of preventative measures. This is something that even the operators of commercial gyms should be aware of and responsible for.

Our study has some important limitations. The cohort of climbers in this study is diverse, as most of the athletes came from local sport climbing areas or gyms, others came from further away. The kind of climbing predominantly performed in the area may influence the injury profile. This bias is constant throughout all our studies, though (14, 15). The previous studies did not report on specific details about the injury cause, such as the exact climbing activity (sub-discipline). Therefore, a detailed comparison on injury frequencies among subdisciplines was not possible. A selection bias cannot be dismissed; as we are very active in treating finger, shoulder and knee injuries in climbers, the patient selection is certainly affected. Nevertheless, this bias is also existing in the previous analysis (36, 37). Thus, constant re-evaluation is important to show trends in injury development and the effects of preventive measures in this context, the implementation of preventive strategies or training programs should be individually assessed.

CONCLUSIONS

The analysis of our recently-treated rock-climbing patients revealed several important findings. Overall, low injury severity in rock climbing and bouldering could be confirmed. Bouldering caused more acute injuries than rope-protected climbing. While common rock climbing related diagnosis, such as finger pulley injuries or epicondylitis decreased in frequency, other complaints (e.g. knee injuries) increased significantly. Despite all efforts, epiphyseal finger injuries in young climbers increased further. Therefore, more educational efforts and specific training are necessary to assure an early detection and treatment, thus avoiding long-term consequences.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (38).

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A Review of Head Injury and Impact Biomechanics in Recreational Skiing and Snowboarding

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SUMMARY

Background. Skiing and snowboarding are popular competitive and recreational sports with associated head injury risks from impact hazards. Understanding head injury hazards and risks in snow sports can inform injury prevention measures, such as helmets, education and environment design of runs and terrain park features, to manage injury risk.

Aim. To identify and discuss (a) the proportion and incidence of head injuries and effectiveness of helmets, (b) circumstances, situational events and characteristics of head injuries and (c) head impact biomechanics in recreational skiing and snowboarding.

Methods. A narrative literature review was performed.

Results. Head injuries comprise up to 38% and 29% of all injuries in skiing and snowboarding, respectively. Skull fractures were found to comprise nearly half of all moderate to severe head injuries in alpine sports across all studies. The most common intracranial injury in skiing and snowboarding was cerebral contusion and subdural haematoma, respectively. Fatal head injuries in skiing are rare with an incidence of approximately one death per one million skier-visits and less than 1% of all skiing head injuries resulted in death. The majority of head injuries were sustained by novice and intermediate level skiers and snowboarders during falls on mild or moderate gradient slopes. Head injury cases occurred in terrain parks were more common in snowboarders than skiers. Fall-related head injuries to skiers are typically in the forward direction with an impact to the front of the head, whereas snowboarders fall rearward and impact the occipital region. Helmet use has increased in recent years, but recent studies have observed an unexpected reduction of the protective effect of helmets in skiing and snowboarding. Alpine sports helmet standards require linear drops onto rigid anvils, but the correlation with snow surfaces is unknown and no helmet standard requires an oblique impact test. Significant protective effects of helmets have been found for collisions and falls onto hard snow.

Conclusions. Alpine sport helmet performance standards should more closely reflect the boundary conditions of impacts to skiers and snowboarders associated with head injury. Administrative and engineering controls may also reduce the risk of head injury in skiing and snowboarding.

KEY WORDS

Head injury; helmet; impact biomechanics; skiing; snowboarding; snow sports

INTRODUCTION

Professional skiing and snowboarding are physically demanding sports involving high speeds, large jumps, technical manoeuvres and equipment specific to each event. In contrast, recreational alpine sports encompass a wide range of ages, skill levels, equipment, environments and hazards. Rigorous long-term injury surveillance programs have been established for professional skiing and snowboarding, which have identified the injury profile of professional athletes differs from recreational skiers and snowboarders (1,2). In addition, high-quality footage of crashes during professional skiing and snowboarding events has enabled detailed investigations of head injuries (3-5). Such detailed injury investigations are limited in the recreational setting. Understanding head injuries in alpine sports can inform injury prevention measures, such as helmets, education and environment design of runs and terrain park features, to reduce head injury risk. Therefore, the purpose of the current review is to identify and discuss (a) the proportion and incidence of head injuries and effectiveness of helmets, (b) circumstances, situational events and characteristics of head injuries and (c) head impact biomechanics in recreational skiing and snowboarding.

HEAD INJURIES

Incidence

Hentschel et al. (6) estimated the incidences of head injuries as 5 per one million skiers and 4 per one million snowboarders. In contrast, Hagel et al. (7) estimated the incidence as 25.9 and 73.4 head injuries per one million skiers and snowboarders, respectively. Similarly, Corra et al. (8) estimated that there were 36 hospitalisations due to head injury per one million skier-days. In a recent study, Dickson et al. (9) analysed alpine sport injuries in Western Canada from 2008 to 2013 and reported the average head injury incidence as 0.2 per 1000 skier-visits.

Head injuries in skiing and snowboarding comprise 5-38% and 5-29% of all injuries, respectively (**table I**). Several studies have analysed head injuries in skiing and snowboarding from different time periods (10,11). Shealy et al. (10) compared head injuries in 1990, 2000 and 2010, but found no decrease over time. In contrast, another study by Shealy et al. (12), head injuries were found to decline from 8.4% to 6.8% of all head injuries over 17 ski seasons. More recently, Sulheim et al. (11) reported that 17.6% of all injuries in skiing and snowboarding were head inju-

Table I. Head injuries as a percentage of all injuries in skiing and snowboarding.

Study	Country	Years	Method	Sport	n	Percentage of all injuries	
						Head	Concussion
Lipskie (2000)(16)	Canada	1996-1997	Ski patrol reports	Ski	4226	8%	
				Snowboard	2501	10%	
Machold et al. (2000) (17)	Austria	1996-1997	School student questionnaire	Snowboard	152	11%	5%
Dohjima et al. (2001)(18)	Japan	1988-1997	Hospital admissions	Ski	4895	10%	
				Snowboard	1776	8%	
Drulec et al. (2001)(19)	Canada	1990-1998	Hospital admissions (paediatric)	Snowboard	118	8%	
Federiuk et al. (2002) (20)	USA	1992-1999	State-wide trauma registry	Ski	67	38%	
				Snowboard	31	29%	
Langran et al. (2002) (21,22)	Scotland	1999-2002	Ski patrol reports	Ski	1095	15%	5%
				Snowboard	567	14%	5%
Bridges et al. (2003)(23)	Canada	1999-2000	Ski patrol reports	Ski	823	11%	11%
				Snowboard	434	14%	
Hagel et al. (2003)(7)	Canada	1991-1999	Canadian Hospitals Injury Reporting and Prevention Program (CHIRPP) (paediatric)	Ski	5410	16%	
				Snowboard	3177	12%	

Table I. Continues

Study	Country	Years	Method	Sport	n	Percentage of all injuries	
						Head	Concussion
Pogorzelski et al. (2003)(24)	Australia	1990-1995, 1997-2002	Ski patrol reports	Ski	5334	8%	4%
				Snowboard	1770	9%	6%
Skokan et al. (2003)(25)	USA	1996-2000	Hospital admissions (paediatric)	Ski	72	19%	8%
				Snowboard	26	31%	25%
Corra et al. (2004)(8)	Italy	2001-2002	Hospital admissions	Ski	1003	15%	
				Snowboard	331	17%	
Yamagami et al. (2004)(26)	Japan	1992-1999	Hospital admissions	Snowboard	3102	18%	
Xiang et al. (2005)(27)	USA	2002	National Electronic Injury Surveillance System (NEISS)	Ski	77,300	16%	
				Snowboard	62,000	17%	
Emery et al. (2006)(28)	Canada	2003-2004	School student questionnaire	Snowboard	142	27%	19%
Ekeland et al. (2008)(29,30)	Norway	2004-2006	Ski patrol reports	Ski	4575	15%	
				Snowboard	2746	14%	
Hayes et al. (2008)(31)	USA	1999-2006	Level I trauma centre registry (paediatric)	Ski	22	36%	
				Snowboard	57	25%	
Sakamoto et al. (2008)(32)	Japan	2000-2005	Medical centre admissions	Ski	1240	5%	
				Snowboard	2220	7%	
Wasden et al. (2009)(33)	USA	2001-2006	Hospital admissions	Ski	794	14%	4%
				Snowboard	348	22%	7%
Brooks et al. (2010)(34)	USA	2000-2005	Ski patrol reports	Ski	508	8%	6%
				Snowboard	9273	12%	10%
Ekeland et al. (2010)(35)	Norway	2006-2008	Ski patrol reports	Ski	5146	14%	
				Snowboard	2447	16%	
Ogawa et al. (2010)(36)	Japan	1996-2008	Hospital admissions	Snowboard	18,791	19%	
Ekeland et al. (2012)(37)	Norway	2008-2010	Ski patrol reports	Ski	6036	14%	
				Snowboard	202	14%	
Kim et al. (2012)(38)	USA	1988-2006	Medical centre admissions (paediatric)	Ski			5%
				Snowboard			5%
			Medical centre admissions (adult)	Ski			3%
				Snowboard			4%
Selig et al. (2012)	Austria	2006-2007	Attended by Helicopter Emergency Medical Service (HEMS) (paediatric)	Ski	749	21%	
				Snowboard	117	22%	
Russell et al. (2014)(39)	Canada	2008-2010	Ski patrol reports	Snowboard	379	14%	11%
Ehrnthaller et al. (2015)(40)	Germany	2005-2012	Hospital admissions	Snowboard	186	5%	
Shealy et al. (2015)(12)	USA	1995-2012	Medical centre admissions	Ski	6296	7%	3%
Shealy et al. (2015)(10)	USA	2010-2011	Medical centre admissions	Ski	13,145	8%	3%
				Snowboard		13%	5%

Table I. Continues

Study	Country	Years	Method	Sport	n	Percentage of all injuries	
						Head	Concussion
Stenroos et al. (2015)(41)	Finland	2010-2011	Ski patrol reports	Ski	1991	15%	
				Snowboard	893	12%	
Basques et al. (2016)(42)	USA	2011-2012	American College of Surgeons (ACS) National Trauma Data Bank (NTDB)	Ski	3351	20%	
				Snowboard	2704	26%	
Weber et al. (2016)(43)	Europe	1993-2012	German Trauma Society Register	Ski	373	22%	
				Snowboard	52	25%	
Dickson et al. (2017)(9)	Canada	2008-2013	Ski patrol reports	Ski, snowboard	82,124	9%	8%
Van Laarhoven et al. (2017)(44)	The Netherlands	2012-2014	Hospital admissions	Ski	232	13%	
				Snowboard	411	11%	
Summers et al. (2017)(45)	Australia	2005-2015	Ski patrol reports (paediatric)	Ski	3821	7%	
				Snowboard	2422	6%	
Basques et al. (2018)(46)	USA	2011-2012	American College of Surgeons (ACS) National Trauma Data Bank (NTDB)	Ski	3351	20%	
				Snowboard	2704	26%	
Ekeland et al. (2019)(47)	Norway	2010-2012	Ski patrol reports	Ski	3569	15%	
				Snowboard	1236	13%	

ries. For youth, head injuries in skiing and snowboarding comprise 7-36% and 6-31% of all injuries, respectively.

CONCUSSION

Concussions are currently a head injury of concern in sports (13), particularly skiing and snowboarding as they comprise 3-8% and 5-25% of all injuries, respectively (**table I**). Specifically, concussions represent 31-77% and 32-83% of all head injuries in skiing and snowboarding, respectively. The accuracy of the diagnosis of concussions can vary across studies. For example, Shealy et al. (10) found that concussions represented between 6% and 11% of all skiing and snowboarding injuries according to ski patrol reports, respectively, but medically diagnosed concussions represented only 3% and 5% of all skiing and snowboarding injuries, respectively. In a recent study, Gil et al. (14) reported the incidence of concussion for skiers was 9.8 concussions per one million skier-seasons. The incidence of 12.7 concussions per one million snowboarder-seasons was significantly higher. Gil et al. (14) also reported that the concussion incidence for youth and males was higher than for adults and females, respectively. Similarly, Bergmann et al. (15) reported that youth snowboarders had a greater likelihood of sustaining a concussion compared to youth skiers.

MODERATE TO SEVERE HEAD INJURIES

Several studies have reported the nature of moderate to severe head injuries in recreational skiing and snowboarding (**table II**). Across studies, skull fractures comprised 46% of all moderate to severe head injuries: skiing, 53%; snowboarding, 40%. Some studies reported types of skull fractures as a proportion of moderate to severe head injuries in skiing and snowboarding: basilar skull fractures, 20-27%; linear skull fractures, 10-19%; depression skull fractures, 7% (6,48,49).

The most common intracranial injury in skiing was cerebral contusion, which was found to comprise 22% of all moderate to severe head injuries across studies. In contrast, subdural haematoma comprised 27% of all moderate to severe head injuries in snowboarding across studies. Subarachnoid, epidural and intracerebral haematoma are relatively uncommon in alpine sports comprising 9%, 7% and 2% of all moderate to severe head injuries across studies, respectively. Interestingly, Levy et al. (48) reported diffuse axonal

Table II. Moderate to severe head injuries in recreational skiing and snowboarding.

Study	Country	Years	Method	Sport	Moderate-severe head injury						
					n	Fracture	SDH	SAH	EDH	ICH	Contusion
Diamond et al. (2001)(50)	USA	1994-1997	State-wide TBI database	Ski	118	24%			39%		
Fukuda et al. (2001)(51)	Japan	1994-1999	Hospital admissions	Ski	46	50%	11%	13%	4%	2%	15%
				Snowboard	49	31%	35%	10%	2%	0%	16%
Hentschel et al. (2001)(6)	Canada	1992-1997	Provincial trauma registry	Ski	34	41%	6%		15%		18%
				Snowboard	24	38%	8%		17%		25%
Levy et al. (2002)(48)	USA	1982-1998	Trauma centre registry	Ski (83%), snowboard (17%)	265	39%	9%		9%	8%	28%
Nakaguchi et al. (2002)(52)	Japan	1995-2000	Hospital admissions	Snowboard	48	15%	38%	17%	6%		21%
Skokan et al. (2003)(25)	USA	1996-2000	Trauma centre admissions (paediatric)	Ski	11	36%			64%		
				Snowboard	5	0%			100%		
Siu et al. (2004)(49)	Australia	1994-2002	Hospital admissions	Ski	18	39%	11%	11%	6%	6%	28%
				Snowboard	10	60%	10%	10%	10%	0%	10%
Fukuda et al. (2007, 2008)(53,54)	Japan	1999-2003	Hospital admissions	Snowboard	88	61%			39%		
Simson et al. (2008)(55)	Canada	1986-1995	Various	Ski	24	29%					23%
Wasden et al. (2009)(33)	USA	2001-2006	Hospital admissions	Ski	87	29%	13%	17%			28%
				Snowboard	44	9%	16%	18%			41%
Fukuda (2011)(56)	Japan	1992-2007	Hospital and medical centre admissions	Ski	54		24%		2%		28%
Koyama et al. (2011)(57)	Japan	1999-2008	Neurosurgery examinations	Snowboard	165	47%	29%	10%	4%		8%
Rughani et al. (2011)(58)	USA	2003-2009	Level I trauma centre registries	Ski (46%), snowboard (54%)	74	47%	12%	15%	4%		19%
Corra et al. (2012)(59)	Italy	2001-2005	Hospital admissions	Ski (88%), snowboard (12%)	108	31%	6%	17%	24%		22%
Shealy et al. (2015)(12)	USA	1995-2012	Medical centre admissions	Ski	438	69%					

SDH: subdural haematoma. SAH: subarachnoid haematoma. EDH: epidural haematoma. ICH: intracerebral haematoma.

injury comprised 8% of all moderate to severe head injuries in skiing and snowboarding.

FATAL HEAD INJURIES

Skiing has long been associated with fatal head injuries 60-64, which includes the deaths of celebrities, such as Sonny Bono and Natasha Richardson. Although head injury has been identified as the primary cause of death in 41-53% of all traumatic fatalities occurring on the slopes (65-67), fatal head injuries in skiing are rare with an incidence of approximately one death per one million skier-visits (12). In addition, less than 1% of all skiing head injuries end in death (12). Coronial inquests have been conducted to investigate fatal head injuries in alpine sports in New Zealand (68) and Canada (67).

LIMITATIONS OF PREVIOUS RESEARCH

There are several limitations associated with previously published research regarding head injuries in skiing and snowboard, most notably the definitions of injuries. The lack of a consistent definition for concussion throughout the literature is well known. The Consensus Statements on Concussion in Sport have attempted to provide a consistent definition for clinicians and researchers (13). In addition, the definition of moderate to severe head injury varies throughout the literature, e.g. positive neuroimaging finding, hospitalisation or simply head injuries that are considered 'non-minor'. Although not specified within studies, it is likely moderate to severe head injuries are defined similar to the Abbreviated Injury Scale (AIS) definitions (69).

Another limitation is the method of data collection, e.g. self-reported questionnaires. Trauma registries and admission records of patients to hospitals and medical centres are considered reliable, but may not contain complete information for each patient. One quarter of studies relied upon ski patrol reports, which have been found to be a reliable source of information on risk factors for skiing and snowboarding compared to follow-up information (70). Lastly, a lack of prospective injury surveillance studies exists, which have been successfully implemented at the professional level (1,2), but is substantially more difficult in a recreational setting.

HELMETS

At the turn of the century, helmet use in skiing and snowboarding was less than 20% (30,71-73), which has subsequently increased to over 60% since 2010 (9-11,37,74,75). Youth skiers and snowboarders are more likely to wear helmets compared to adults (73). In addition, younger children are more likely to use helmets compared to adolescents (15,76). In 1999, the United States Consumer Product Safety Commission (CPSC) investigated skiing and snowboarding head injuries and concluded that helmets reduce the risk of such injuries (77). Subsequent systematic reviews supported the protective value of helmets in skiing and snowboarding (78-80). Skinner et al. (67) analysed 45 alpine sport-related deaths in Ontario from 1991 to 2012. Of the 25 head injury cases an expert review team determined that a certified helmet would have prevented death in 36% of cases, probably prevented death in 24% of cases and possibly prevented death in 16% cases. In contrast, Baschera et al. (81) found no significant decrease in severe traumatic brain injury among skiers despite an increase in helmet use. Bergmann et al. (15) found no significant difference between concussion incidence for helmeted and non-helmeted youth skiers and snowboarders. Such findings were supported by Milan et al. (82) with helmet use not significantly influencing head injury in youth skiers and snowboarders, but helmeted patients admitted to the ICU had significantly lower head injury severity compared to non-helmeted patients. Sulheim et al. (11) observed an unexpected reduction in the protective effect of helmets in skiing and snowboarding over time. More recently, Porter et al. (83) found helmet use was associated with higher injury severity although helmet users were less likely to sustain a skull fracture. For helmets to reduce the risk of head injury, the mechanisms of head injuries are required to be well understood (84,85).

HEAD IMPACT CHARACTERISTICS

Demographics

Studies of head injury in skiing and snowboarding have reported that 58-84% were male (6,9,15,48-54,57-59,86-94). It is unknown if such a finding is due to skiing and snowboarding being more popular amongst males, whether males engage in higher-energy activities, which may be at or beyond skill capabilities. For head injured skiers and snowboarders, mean ages ranged from 23 to 29 years with the youngest and oldest being 2 and 83 years, respectively (6,48-54,90,92). Over 80% of all cases are sustained by skiers and snowboarders older than 15 years (59,93) and few studies have reported solely on paediatric head injuries in skiing and snowboarding (15,58,95).

Skill levels of head injured skiers and snowboarders have been reported in several studies (**table III**), but no standardised definitions were used by such studies. The majority of skiing head injuries were sustained by novice (33-50%) and intermediate (42-45%) level skiers. Similarly, the majority of snowboarding head injuries were sustained by novice (31-57%) and intermediate (26-49%) level snowboarders. Only 8-23% and 5-19% of head injuries were sustained by advanced level skiers and snowboarders, whereas recent studies of head injured skiers and snowboarders reported that 28-38% and had an advanced skill level.

INCIDENT LOCATION

Several studies have reported the incident location of recreational skiing and snowboarding head injury cases (**table IV**). The majority of head injuries occurred on slopes (62-97%), which have mild and moderate gradients. Although few

Table III. Skill level of recreational skiing and snowboarding head injury cases.

Study	Country	Years	Method	Sport	N	Skill level		
						Novice	Intermediate	Advanced
Sakai et al. (1997, 1999)(96, 97)	Japan	1988-1998	Hospital admissions	Ski	557	50%	42%	8%
				Snowboard	363	55%	40%	5%
Nakaguchi et al. (1999)(90)	Japan	1995-1997	Hospital admissions	Ski	158	36%	44%	20%
				Snowboard	143	31%	49%	19%
Fukuda et al. (2001)(51)	Japan	1994-1999	Hospital admissions	Ski	442	39%	43%	18%
				Snowboard	634	52%	40%	9%
Nakaguchi et al. (2002)(52)	Japan	1995-2000	Hospital admissions	Snowboard	38	57%	26%	17%
Wilkins (2003)(91)	USA	1999-2001	Ski patrol reports	Snowboard	58	34%	48%	17%
Fukuda (2011)(56)	Japan	1992-2007	Hospital and medical centre admissions	Ski	1296	33%	45%	23%
Koyama et al. (2011)(57)	Japan	1999-2008	Neurosurgery examinations	Snowboard	2367	41%	59%	
Bailly et al. (2017)(94)	France	2013-2015	Medical centre and hospital admissions	Ski (81%), snowboard (19%)	366	12%	49%	38%
Dickson et al. (2017)(9)	Canada	2008-2013	Ski patrol reports	Ski (42%), snowboard (58%)	7549	38%	33%	28%

Table IV. Incident location of recreational skiing and snowboarding head injury cases.

Study	Country	Years	Method	Sport	N	Slope			Terrain park
						Mild (<10°)	Moderate (10-20°)	Steep (>20°)	
Sakai et al. (1997, 1999) (96,97)	Japan	1988-1998	Hospital admissions	Ski	557	36%	48%	17%	
				Snowboard	363	39%	48%	13%	
Machold et al. (2000)(17)	Austria	1996-1997	School student questionnaire	Snowboard	17	74%			
Fukuda et al. (2001)(51)	Japan	1994-1999	Hospital admissions	Ski	442	35%	51%	12%	3%
				Snowboard	634	33%	29%	6%	31%
Nakaguchi et al. (2002)(52)	Japan	1995-2000	Hospital admissions	Snowboard	38	41%	30%	0%	30%
Fukuda et al. (2007, 2008) (53,54)	Japan	1999-2003	Hospital admissions	Snowboard	1190				38%
Greve et al. (2009)(92)	USA	2002-2004	Medical centre admissions	Ski (53%), snowboard (47%)	1002				19%
Moffat et al. (2009)(100)	USA	2006-2007	Level I trauma centre registry	Ski, snowboard	94				26%
Brooks et al. (2010)(34)	USA	2000-2005	Ski patrol reports	Ski	443				24%
				Snowboard	1133				45%
Ruedl et al. (2010)(93)	Austria	2008-2009	Ski patrol reports	Ski (78%), snowboard (22%)	277	37%	54%	9%	0%

Table IV. Continues

Study	Country	Years	Method	Sport	N	Slope			Terrain park
						Mild (<10°)	Moderate (10-20°)	Steep (>20°)	
Fukuda (2011) (56)	Japan	1992-2007	Hospital and medical centre admissions	Ski	1296	31%	43%	16%	10%
Koyama et al. (2011)(57)	Japan	1999-2008	Neurosurgery examinations	Snowboard	2367	30%	27%	4%	36%
Stenroos et al. (2018)(101)	Finland	2006-2015	Hospital admissions	Ski (74%), snowboard (26%)	72				39%

Note: Moffat et al. (100) reported head/face injuries. Ruedl et al. (93) classified slopes as per the European piste classification system (102).

injuries occurred on steep slopes, relatively more head injuries occurring on steep slopes were reported for skiing (9-16%) compared to snowboarding (0-6%). Ruedl et al. (98) investigated the factors associated with injuries occurring on slope intersections and found no significant difference between the proportion of head/neck injuries sustained on slope intersections (12.3%) compared to general slopes (12.4%). For skiing, less than 25% of all head injury cases were reported to have occurred in terrain parks, whereas 30-45% of all snowboarding head injury cases occurred in terrain parks. Head injuries in skiing and snowboarding as a proportion of all injuries have been found to be greater in terrain parks compared to slopes (34,98-100).

In terms of the skill level of head injured snowboarders, Nakaguchi et al. (52) reported that all novices were on mild slopes. In contrast, almost all head injured intermediate and advanced snowboarders were on moderate slopes (89%). Koyama et al. (57) reported that 54% of head injured novice snowboarders were on mild slopes and 62% of all head injured intermediate and advanced snowboarders were on moderate or steep slopes.

Few studies reported the condition of the snow for head injury cases (52,93,103) Sakai et al. (103) reported that the snow was 'packed' or 'ice and debris' for skiing and snowboarding in 56% and 64% of cases, respectively. More recent studies have reported that the snow was 'hard' and 'iced' for 75% of head injury cases in skiing and snowboarding, whereas the snow was 'soft' in only 25% of cases (52,93).

SITUATIONAL EVENT

In terms of gross biomechanical description (104), several studies have reported the situational event of recreational skiing and snowboarding head injury cases (**table V**). Most head injuries in skiing are sustained during falls (36-74%) followed by collisions (20-62%), whereas fewer head injuries were sustained during jumps (1-31%). The majority of snowboarding head injuries are sustained during falls (38-63%) followed by jumps (14-38%) and collisions (10-29%).

FALLS

Burtscher et al. (109) investigated the predictors of falls in skiing and snowboarding with younger age and alcohol consumption reported as risk factors. Similarly, Konik et al. (110) investigated fall-related head injuries and identified that skiers and snowboarders younger than 40 years were most affected and had the most severe intracranial lesions and/or skull fractures. The fall incidence of fall-related head injuries as 0.2 per 1000 skier-days. More recently, Philippe et al. (111) found that younger age and lower skills were predictive of skiing and snowboarding falls. In addition, soft snow conditions and alcohol consumption were found to be predictors for falls in skiing and snowboarding, respectively. The incidence of falls was identified as 0.08 and 0.43 per hour for skiing and snowboarding, respectively, which was substantially lower than data collected a decade prior (109). Phillippe et al. (111) attributed the decrease in fall incidence to improvements in skiing and snowboarding equipment and slope preparation. Stenroos et al. (101) reported 90% of falls by skiers and snowboarders that resulted in head injury occurred on slopes and the remaining 10% occurred in the terrain park.

Few studies have reported the direction of fall for skiers and snowboarders. For skiers, Nakaguchi et al. (90) reported that falls causing head injuries were most commonly in the forward direction (54%), followed by the rearward (35%) and sideward (10%) directions. More recently, Bailly et al. (94) also reported the forward direction to be the most common fall

Table V. Situational event of recreational skiing and snowboarding head injury cases.

Study	Country	Years	Method	Sport	N	Situational event		
						Fall	Collision	Jump
Harris (1983)(105)	USA	1975-1979	Various	Ski	82	57%	35%	7%
Harris (1989)(106)	USA	1975-1988	Various	Ski	374	40%	47%	13%
Lindsjö et al. (1985)(88)	Sweden	1979-1982	Hospital admissions	Ski	159	74%	25%	1%
Myles et al. (1992)(89)	Canada	1983-1988	Hospital admissions	Ski	88	51%	44%	
Sakai et al. (1997, 1999)(96,97)	Japan	1988-1998	Hospital admissions	Ski	557	36%	62%	1%
				Snowboard	363	63%	10%	26%
Nakaguchi et al. (1999)(90)	Japan	1995-1997	Hospital admissions	Ski	158	61%	38%	1%
				Snowboard	143	49%	20%	31%
Diamond et al. (2001)(50)	USA	1994-1997	State-wide TBI database	Ski	118		43%	
Fukuda et al. (2001)(51)	Japan	1994-1999	Hospital admissions	Ski	442	55%	43%	2%
				Snowboard	634	51%	19%	30%
Hentschel et al. (2001)(6)	Canada	1992-1997	Provincial trauma registry	Ski	40	42%	42%	16%
				Snowboard	14	57%	29%	14%
Levy et al. (2002)(48)	USA	1982-1998	Level I trauma centre registry	Ski (83%), snowboard (17%)	350	40%	61%	
Nakaguchi et al. (2002)(52)	Japan	1995-2000	Hospital admissions	Snowboard	38	58%	21%	21%
Fukuda et al. (2004)(107)	Japan	2000-2003	Hospital admissions	Ski	137	42%	43%	7%
				Snowboard	1146	40%	16%	38%
Siu et al. (2004)(49)	Australia	1994-2002	Hospital admissions	Ski	15	47%	20%	31%
				Snowboard	9	38%	25%	28%
Greve et al. (2009)(92)	USA	2002-2004	Medical centre admissions	Ski (53%), snowboard (47%)	1002	74%	23%	
Ruedl et al. (2010)(93)	Austria	2008-2009	Ski patrol reports	Ski (78%), snowboard (22%)	277	79%	21%	
Fukuda (2011)(56)	Japan	1992-2007	Hospital and medical centre admissions	Ski	1296	48%	42%	10%
Koyama et al. (2011)(57)	Japan	1999-2008	Neurosurgery examinations	Snowboard	2367	46%	18%	34%
Stenroos et al. (2015)(41)	Finland	2006-2012	Ski resort emergency system	Ski (39%), snowboard (61%)	94	16%	27%	57%
Stuart et al. (2016)(108)	Canada	2009-2014	Hospital admissions	Ski (39%), snowboard (61%)	763	54%	15%	17%
Bailly et al. (2017)(94)	France	2013-2015	Medical centre and hospital admissions	Ski	295	53%	34%	13%
				Snowboard	71	56%	20%	24%
Stenroos et al. (2018)(101)	Finland	2006-2015	Hospital admissions	Ski (74%), snowboard (26%)	72	32%	11%	47%

type for skiers (35%) followed by the sideward (23%) and rearward (18%) directions. In addition, ‘crossing skis’ and ‘spreading skis’ were reported as the fall type in 15% and 5% of cases, respectively. In contrast, most falls causing head injuries to snowboarders were most commonly in the rearward direction (48-79%) followed by the forward (9-45%) and sideward (6-12%) directions (52,90,94). Rearward falls in snowboarding typically occur when the rear edge of the snowboard catches on the snow, which is known as the ‘rear edge phenomenon’ (51,52,57,90) Sakai et al. (103) reported that fall-related head injuries in snowboarding were due to rear edge catches in two-thirds of cases (66%). Uzura et al. (112) detailed a case report regarding a subdural haematoma sustained by a snowboarder after impacting the occiput during a rearwards fall after catching an edge on a steep slope.

COLLISIONS

Reports from older studies are extremely varied for collision-related head injuries in skiing and snowboarding (**table VI**). More recent studies have reported that collision-related head injuries in skiing are fairly evenly distributed between collisions involving another person (50-55%) and collisions with fixed objects (45-50%) (41,94). In contrast, collision-related head injuries in snowboarding typically involve another person (71-100%) and collisions with fixed objects are less common (0-29%) (31,33). Stenroos et al. (101) reported 86% of collisions with fixed objects occurred in an urban setting and the remaining 14% occurred in terrain parks. In contrast, all collisions involving another person occurred on slopes.

Table VI. Collision types of recreational skiing and snowboarding head injury cases.

Study	Country	Years	Method	Sport	N	Collision			
						Person		Object	
						Skier	Snow-boarder	Tree	Other
Oh et al. (1979)(86)	Switzerland	1974-1979	Neurosurgery examinations	Ski	32	24%		76%	
Lang et al. (1980) (113)	Austria	1976-1978	Medical centre admissions	Ski	243	69%		8%	19%
Lindsjö et al. (1985)(88)	Sweden	1979-1982	Hospital admissions	Ski	159	50%		35%	15%
Lystad (1989) (114)	Norway	1982-1986	Medical centre admissions	Ski	158	28%		26%	46%
Myles et al. (1992) (89)	Canada	1983-1988	Hospital admissions	Ski	88	16%		49%	35%
Fukuda et al. (2001)(51)	Japan	1994-1999	Hospital admissions	Ski	442	59%	34%	4%	4%
				Snowboard	634	25%	64%	7%	4%
Hentschel et al. (2001)(6)	Canada	1992-1997	Provincial trauma registry	Ski	40	13%		81%	6%
				Snowboard	14	0%		50%	50%
Fukuda et al. (2004)(107)	Japan	2000-2003	Hospital admissions	Ski	137	29%	63%		8%
				Snowboard	1146	9%	82%		9%
Fukuda (2011) (56)	Japan	1992-2007	Hospital and medical centre admissions	Ski	1296	50%	42%		8%
Stenroos et al. (2015)(41)	Finland	2006-2012	Ski resort emergency system	Ski	37	50%			50%
				Snowboard	57	100%			0%
Bailly et al. (2017) (94)	France	2013-2015	Medical centre and hospital admissions	Ski	295	55%			45%
				Snowboard	71	71%			29%
Stenroos et al. (2018)(101)	Finland	2006-2015	Hospital admissions	Ski (74%), snowboard (26%)	72	53%			47%

COLLISIONS WITH OBJECTS

Nachbauer et al. (115) reported that skiers determined responsible for collisions and victims of collisions sustained head injuries in 54% and 39% of skier-to-skier collisions, respectively. In a subsequent study, Burtscher et al. (116) reported that approximately 38% of all skiers involved in a collision sustained a head injury. For ski collisions involving trees, Frermood et al. (117) found a significantly greater proportion of intracranial head injuries and/or skull fractures compared to skiers that did not collide with a tree. More recently, Bailly et al. (94) found that almost half of serious head injuries (48%), with Glasgow Coma Scores of less than 13, involved collisions with objects. In addition, head injuries from collisions with objects were found to occur on novice or intermediate slopes (62%). Stenroos et al. (101) reported that only 14% of collisions with fixed objects that resulted in head injury occurred in terrain parks and the remaining 86% occurred in urban environments, which involves skiers and snowboarders sliding on handrails and jumping off structures.

COLLISIONS WITH PERSONS

In an early study, Oh et al. (118) investigated head injuries sustained from skier-to-skier collisions and found that typically one skier was impacted to the side and sustained a severe head injury, whereas the other skier was impacted to the front and sustained only a minor, or no, head injury. Nachbauer et al. (115) reported that 54% and 39% of collision victims and skiers responsible for collisions sustained head injuries, respectively. In contrast, Burtscher et al. (116) reported that 30% of collision victims and 46% of skiers

Table VII. Recreational skiing and snowboarding head injuries sustained in terrain parks.

Study	Country	Years	Method	Sport	Injury	N	Percentage of all injuries		Ratio effect estimate	
							TP	Non-TP	Value (95% CI)	Analysis
Goulet et al. (2007) (99)	Canada	2001-2005	Ski patrol reports	Ski	Head/neck (all)	5047	24%	17%	1.35 (1.22-1.50)	Adjusted OR
					Head/neck (severe)	2077	11%	7%	1.21 (1.01-1.45)	
				Snowboard	Head/neck (all)	5378	24%	21%	1.00 (0.93-1.07)	
					Head/neck (severe)	2864	12%	11%	0.95 (0.84-1.08)	
Moffat et al. (2009) (100)	USA	2006-2007	Level I trauma centre registry	Ski, snowboard	Head/neck	94	33%	27%		
					Closed head injury	35	14%	10%		
					Concussion	40	15%	11%		
					Intracranial haematoma	4	0%	2%		
					Skull/facial fracture	15	4%	5%		
Brooks et al. (2010) (34)	USA	2000-2005	Ski patrol reports	Ski	Head	443	17%	7%	1.70 (1.32-2.18)	Multi-variable RR
					Concussion	341	16%	5%	2.13 (1.61-2.82)	
				Snowboard	Head	1133	15%	10%	1.26 (1.10-1.45)	
					Concussion	947	15%	8%	1.59 (1.36-1.85)	
Ruedl et al. (2013) (98)	Austria	2008-2009	Ski patrol reports	Ski, snowboard	Head/neck	297	19%	12%	1.6 (1.0-2.5)	Uni-variate OR

Goulet et al. (99) defined severe injury as per Lipskie (16). TP: terrain park. CI: confidence interval. OR: odds ratio. RR: Risk ratio.

responsible for collisions sustained head injuries. More recent studies have identified that collisions with other skiers and snowboarders comprise 10-25% of all head injury cases (94,119). Bailly et al. (94) also identified that collisions with other skiers and snowboarders particularly affected youth, females and lower-skilled skiers and snowboarders. In 62% of collision-related head injury cases involving other skiers and snowboarders, Bailly et al. (94) found that the 'impacting' skier or snowboarder was moving at high speed while the 'impacted' skier or snowboarder was stationary or moving at low speed (94). Not surprisingly, Stenroos et al. (101) reported all collisions involving another person occurred on slopes.

JUMPS

The first known terrain park was built in 1986 at Snow Summit, CA and the first known terrain park open to the public was built in 1991 at Bear Mountain, CA (120). Terrain parks are specific areas of alpine sport resorts, which contain features such as jumps that allow skiers and snowboarders to perform maneuvers and tricks. Prior to the introduction of terrain parks, jumping was actively discouraged within resorts. Therefore, skiers and snowboarders built jumps outside alpine sport resorts or secretly inside the boundaries (121). Over the last three decades, the proportion of alpine sport resorts with terrain parks has steadily increased to 94% as of 2010 (122). It is not uncommon for major alpine sport resorts to have multiple terrain parks of varying difficulty (123).

From 1996 to 2001, Fukuda (124) identified a linear increase in the proportion of snowboarding head injuries from jumps: 23% to 33% (R^2=0.98). In contrast, Shealy et al. (10) found no increase in the prevalence or incidence of injury from jumping from 2000 to 2010 despite an increase in terrain parks. The proportion of head injuries has been found to be greater in terrain parks for skiers and snowboarders (**table VII**). Henrie et al. (125) reported the proportion of head and spine injuries sustained in terrain parks was approximately twice double the proportion sustained on general slopes. Interestingly, Bailly et al. (94) found that just over half of all head injuries from jumps were sustained in terrain parks (55%), whereas the remainder were sustained on novice and intermediate slopes (31%) and off-pise (14%). As expected, most jump-related head injuries that involved forward and rearward crashes impacted the facial/frontal (74%) and occipital (72%) regions of the head, respectively (94) Uzura et al. (112) detailed a case report regarding a subdural haematoma sustained by a snowboarder impacting the right temporal region after jumping and falling sideward. Stenroos et al. (101) reported 76% of jump-related head injuries occurred in terrain parks, whereas 21% and 3% occurred in urban environments and on the slopes, respectively.

Terrain parks do not just contain aerial features, but non-aerial features such as boxes, rails and quarter-pipes. Carús et al. (126,127) found that the proportion of head injuries sustained on aerial features of terrain parks by skiers (14%) was higher than for non-aerial features (9%). Similarly, Russel et al. (128) found that the proportion of head injuries sustained on aerial features of terrain parks by snowboarders (15%) was higher than for non-aerial features (9%). More specifically, Russel (129) found that the most common feature on which snowboarders sustained head injuries were jumps (38%) followed by kickers (29%), boxes (10%), quarter-pipes (8%) and half-pipes (6%). Interestingly, Russel (129) reported four cases of concussion, which were sustained by snowboarders in the terrain park, but not on any specific features, i.e. snowboarding between features.

HEAD IMPACT SITE

Few studies have reported the incident location of recreational skiing and snowboarding head injury cases (**table VIII**). For skiing, head impacts causing injury are primarily to frontal (37-56%) and occipital (33-41%) regions. For snowboarding head injury cases, the occiput is the most common impact region (53-68%) followed by the frontal region (16-37%). Relatively few impacts to the temporal (3-18%) and parietal (1-7%) regions cause head injury in skiing and snowboarding.

HEAD IMPACT BIOMECHANICS

Kinematics

To investigate the biomechanics of head impacts in skiing and snowboarding, kinematic boundary conditions are required to be identified, such as the horizontal speed of the skier or snowboarder in the plane of the slope. No studies have reported impact speeds in skiing and snowboarding speeds in regard to head injury crashes, but several studies have reported the general speeds of recreational skiers and snowboarders at resorts (**table IX**). For skiers of all ages and skill levels on all slope difficulty levels, the mean speed was 12.4 m/s with a maximum of 30.1 m/s. For snowboarders of all ages and skill levels on all slope difficulty levels, the mean speed was 11.1 m/s with a maximum of 22.0 m/s. Skiers tend to travel faster than snowboarders. In addition, skiers and snowboarders of higher skill levels tend to travel faster compared to lower skill levels. Dickson et al. (130,131) reported that youth skiers and snowboarders travelled at mean speeds of 12.2 and 11.1 m/s, respectively, which are similar to the mean speeds for

Table VIII. Head impact site for recreational skiing and snowboarding head injury cases.

Study	Country	Years	Method	Sport	N	Sites			
						Frontal	Temporal	Parietal	Occipital
Nakaguchi et al. (1999) (90)	Japan	1995-1997	Hospital admissions	Ski	158	56%	3%	7%	33%
				Snowboard	143	37%	5%	5%	53%
Fukuda et al. (2001)(51)	Japan	1994-1999	Hospital admissions	Ski	442	37%	18%	4%	41%
				Snowboard	634	24%	12%	1%	63%
Nakaguchi et al. (2002) (52)	Japan	1995-2000	Hospital admissions	Snowboard	38	16%	14%	3%	68%
Koyama et al. (2011) (57)	Japan	1999-2008	Neurosurgery examinations	Snowboard	2367	24%	10%	4%	62%

Table IX. Speeds of recreational skiers and snowboarders.

Study	Country	Method	Age	Sport	Observations	Skill	Speed [m/s]		
							Mean	SD	Max
Shealy et al. (2005) (133)	USA	Radar	All	Ski	533	All	12.4		
				Snowboard	117	All	10.8		
Scher et al. (2006) (134)	USA	Radar	All	Snowboard	180	Novice	4.9		
						Intermediate	8.9		16.8
Scher et al. (2008) (132)	USA	Radar	Youth	Ski	107	All	5.2	1.7	12.8
				Snowboard	47	All	5.3	1.9	
Ruedl et al. (2010) (135)	Austria	Radar	All	Ski	1877	All	12.4	3.9	26.4
				Snowboard	223	All	11.3	3.8	20.0
Dickson et al. (2011, 2012)(136,137)	Canada	GPS	All	Ski (96%), snowboard (4%)	98	All	17.3		30.1
					2	Novice	11.7	2.5	21.0
					27	Intermediate	15.3	3.3	21.0
					40	Advanced	18.1	3.2	27.5
					29	Expert	18.3	3.6	30.1
Ruedl et al. (2013) (138) Brunner et al. (2015)(139)	Austria	Radar	All	Ski	416	All	12.6		
					289	Novice, intermediate	11.9	3.5	
					127	Advanced, expert	14.1	4.0	
Dickson et al. (2015, 2016)(130,131)	Not reported	GPS	Youth	Ski	100	All	12.2	4.4	22.8
				Snowboard	58	All	11.1	4.0	22.0
				Ski, snowboard	54	Novice	9.3	3.6	18.5
					37	Intermediate	11.9	3.3	22.0
					46	Advanced	14.6	3.4	20.4

all skiers and snowboarders. An earlier study by Scher et al. (132) reported much slower speeds for youth skiers and snowboarders: 5.2 and 5.3 m/s, respectively.

Greenwald et al. (140) instrumented the helmets of 46 youth snowboarders with the Head Impact Telemetry (HIT) System and 674 sensor events were recorded at a snow resort in the United States during the winter of 2007-2008. More sensor events were recording in the terrain park compared to regular slopes. The highest peak linear and angular head accelerations were 113 g and 9515 rad/s^2;

respectively, whereas 95% of impacts had a peak linear head acceleration of less than 50 g. No concussions were medically diagnosed. A similar study on 107 school skiers and snowboarders at Australian snow resorts during the winters of 2009 to 2011 was conducted by Dickson et al. (131,141,142) The HIT System was coupled with global positioning system (GPS) data to remove false-positives, after which only three impacts head peak linear accelerations greater than 40 g.

FALLS

If a skier or snowboarder falls while stationary, the impact can be idealised as a simple fall from standing height. Head impacts with a purely translational component are often experimentally replicated using a drop test as part of helmet standards (**table X**). A drop test rig comprises a drop tower and carriage with a head form attached. A trixial accelerometer is mounted inside the head form to record the acceleration at the centre of gravity. The helmet is attached to the head form and the carriage is raised to a height that correlates with the desired impact speed. For drops onto a flat anvil, impact speeds range from 4.5 to 6.8 m/s, which correlate to drop heights of 1.03 to 2.36 m. The Snell standards stipulate impact severity in terms of energy (143,144). For an example drop carriage mass of 5 kg, an impact energy of 120 J onto a flat anvil correlates to a drop height of 2.45 m and impact speed of 6.93 m/s. Some standards also require impacts onto hazard anvils, such as hemispherical or edge anvils. Linear head acceleration limits range from 250 to 300 g, which are in the range associated with skull fracture (145-147).

Dickson et al. (9,130,131,142) has repeatedly stated that the speeds of skiers far exceed the impact speeds used in helmet standards and suggested that the impact speed of the standard be increased. In collisions with fixed objects, travel speed is critical. For falls, the travelling speed of a skier or snowboarder is tangential to the slope and does no contribute to the normal component of a fall onto the slope surface, which can be estimated from standing height. As the speed of a skier or snowboarder increases, the impact vector becomes more oblique, whereas the normal component remains unchanged. Similarly, motorcycles in Australia can legally travel up to 110 km/h (30.6 m/s) on some major roads, but the Australian Standard for motorcycle helmets requires a drop test from 2.5 m, which is equivalent to an impact speed of 7.0 m/s. (152) No alpine sport helmet requires an oblique impact test.

To investigate correlation between helmet impacts onto rigid anvils and snow surfaces, studies have performed helmet impacts onto snow surfaces. Dressler et al.[153] investigated the protective potential of a ski helmet, which was certified to the ASTM standard (148). Drop tests at 4 m/s were performed onto soft and hard snow samples with the latter being frozen overnight. For soft snow impacts, no significant differences were found between the helmeted and non-helmeted conditions and all peak linear head

Table X. Standards for Ski and Snowboarding Helmets.

Source	Standard	Title	Year	Impact attenuation		
				Anvil	Severity	Limit [g]
American Society for Testing and Materials	ASTM F2040 (148)	Recreational snow sports	2018	Flat	6.20 m/s	300
				Hemispherical (Ø 96 mm)	4.80 m/s	
				Edge	4.50 m/s	
Canadian Standards Association	CSA Z263.1 (149)	Recreational alpine skiing and snowboarding helmets	2014	Flat	4.50 m/s	250
					5.40 m/s	250
European Committee for Standardization	EN 1077 (150)	Helmets for alpine skiers and snowboarders	2007	Flat	5.42 m/s	250
Fédération Internationale de Ski*	FIS (151)	Crash Helmets	2018	Flat	6.80 m/s	250
Snell Memorial Foundation	Snell RS-98 (143)	Recreational skiing and snowboarding	1998	Flat	100 J	300
				Hemispherical (Ø 96 mm)	80 J	
				Edge		
	Snell S-98 (144)	Skiing and other winter activities	1998	Flat	120 J	300
				Hemispherical (Ø 96 mm)	100 J	
				Edge		

*FIS certified helmets must also meet ASTM F2040 and EN 1077.

form accelerations remained below 42 g. In contrast, hard snow impacts to the crown of the non-helmeted and helmeted head form resulted in peak linear acceleration ranges of 138-165 g and 79-98 g, respectively; therefore, the presence of the ski helmet was found to significantly reduce peak linear head form accelerations by 32-48%. The quality and consistency of snow samples was a limitation and it was suggested that future studies investigate snow hardness at ski resorts.

Numerical models have also been used to investigate head impacts onto snow. Kleiven et al. (154,155) evaluated the performance requirements for the European downhill and super-g ski helmet standard (150). A helmeted Hybrid III head form was dropped onto ski slopes, the acceleration and high-speed video data from which were used to reconstruct the oblique impacts and validate a finite element snow model. In addition, video footage of alpine skiing crashes were collected and analysed to obtain head impact kinematics,[4,155] which indicate that substantial rotational forces are experienced by the head during impacts. One limitation was that the head form was released by hand; therefore, issues with pre-impact rotations were experienced. More recently, Bailly et al. (156) obtained the damping properties of hard and soft snow by performing drop tests on ski slopes using a rigid head form to develop a numerical model. Mean peak linear accelerations for 1.5, 2.0 and 3.0 m simulated drop tests ranged from 72 to 138 g for hard snow and 42 to 81 g for soft snow, respectively.

Simple falls from standing height have been investigated using anthropomorphic test devices (ATDs) (157-159). Similarly, ATDs have been used to simulate rearward falls onto snow slopes resulting in occipital head impact (134,160,161), which has been identified as the situational event of over half of all major head injuries to snowboarders (51,52,57,90). An Hybrid III ATD was accelerated along a cable and released at approximately 8 m/s onto a snow-covered ramp with a gradient of 20°, which was used to replicate a snow slope. For soft snow impacts to the occiput, no significant protective effect was observed in the helmeted tests and all peak linear head form accelerations remained below 83 g for all soft snow impacts and no significant differences were found between the helmeted and non-helmeted conditions. In contrast, icy snow impacts to the occiput of the non-helmeted and helmeted head form resulted in mean peak linear accelerations of 391 g and 162 g, respectively; therefore, the presence of the ski helmet was found to significantly reduce peak linear head form accelerations by a factor of over two. The need to correlate helmet test standards to real-world impacts was identified (161).

Bailly et al. (156) simulated rearward falls of non-helmeted snowboarders, which were previously reconstructed using an ATD (134,160,161). The peak linear head form accelerations were found to be similar for soft snow impacts; however, the numerical simulations underestimated the peak linear acceleration of the ATD head form for the hard snow impacts. A parametric study of rearward snowboarding falls identified that the size of the snowboarder, initial velocity and snow stiffness influenced head injury risks. It was concluded that a relevant impacting surface and more demanding acceleration criteria should be considered for inclusion in performance standards for ski and snowboard helmets.

Although it is possible to alter the magnitude of head form linear acceleration, by altering the drop height, equivalent to an impact onto a snow surface, the duration of the rigid anvil impact will be shorter than the snow surface impact. Once snow surfaces of varying hardness are characteristed, suitable anvils with similar material properties may be used instead of rigid anvils to achieve a similar head form linear acceleration pulse in terms of magnitude and duration. In addition, situation event data could be used to provide sport-specific helmet performance standards, i.e. different standards for ski and snowboarding helmets. For example, a ski helmet standard may include a more severe oblique test to the front of the helmet, whereas a snowboard helmet standard may include a drop test onto the occipital region.

COLLISIONS

In addition to falls, ATDs have also been used to investigate collisions in skiing and snowboarding. Scher et al. (132) used ATDs in a pendulum configuration to replicate skier-to-pole and skier-to-skier frontal impacts. The presence of a helmet was associated with a significant decrease in peak linear head form accelerations for both skier-to-pole and skier-to-skier impacts. Decreases in peak angular head form accelerations were observed for both impact configurations; however, only the results from the skier-to-skier configuration were significant. Muser et al. (162) used ATDs equipped with skis, poles, skiing attire and helmets to reconstruct a 90° impact between two skiers. One skier was stationary and oriented at 90° to the other skier travelling at 8.3 and 13.9 m/s. For the 8.3 m/s impact, the mean peak linear head acceleration for both ATDs was 103 g, which is comparable to the mean peak head accelerations experienced by Australian football players during a concussion impact (163). Surprisingly, mean peak head acceleration for the 13.9 m/s impact was 91 g. However, Muser et al. (162) reported that the head and torso made initial contact for the 8.3 and 13.9 m/s impacts, respectively. Petrone et al. (164) developed an ATD, which was constructed using an ANSI head form and a Hybrid II neck form, to investigate high speed helmeted collisions into safety nets and foam mats (165). Speeds of up to 18.3 m/s were achieved with an 18 m pendulum rig, which resulted in peak head form accelerations of up to 189 g.

Physical reconstructions of collisions have demonstrated that peak linear acceleration of the head form varies depending on the impact object. Similar to impact testing of American football helmets (166), a performance standard test for alpine helmets could incorporate common impacting surfaces, such as poles and other skiers, using a linear impactor. Rotation of a head form during a linear impact test allows for the measurement of rotational kinematics, which have long been associated with diffuse head injuries (167-169).

JUMPS

After instrumenting a snowboarding during jumps, Shealy et al. (170) reported mean resultant linear accelerations of 74.6 g, 3.7 g and 2.5 g at the boot, chest and head, respectively. It was concluded that when the snowboarder lands correctly, the lower limb structure significantly attenuated the impact acceleration. Such a finding supports the results of an early study of human tolerance to vertical impact, in which accelerations of up to 250 g could be absorbed when subjects landed with legs flexed with only slight pain in the lower limbs (171).

Equivalent fall height (EFH), which is the component of point mass velocity normal to the snow surface in terms of distance, has previously been used to assess the landing height of Nordic ski jumpers (172). Although a safe EFH for terrain park jumps has yet to be established, Hubbard et al. (173) reasoned that 1.0 m seemed appropriate and found that jumps can be designed with a EFH of 1.0 m that suit most available sites. EFH is dependent on take-off speed and angle; however, both variables can be affected by 'pop', which occurs when a skier or snowboarder manipulates take-off by jumping or dropping (174). Another consideration is the design of the launch ramp, which should end with a straight section as a concave launch ramp may cause undesirable rotations and involuntary inversion (175,176). Scher et al. (121) investigated the injury potential of a snowboarder landing inverted using an ATD, which was lifted above a snow surface. For each drop, the ATD was released and made contact with a horizontal bar, which induced rearwards rotation. The snow surface angle and ATD fall distance were altered to provide a range of EFHs from 0.23 to 1.52 m. Peak linear and angular head accelerations of 52-142 g and 1920-5091 rad/s^2, respectively, were recorded across trials and are associated with concussion (163), but below acceleration levels associated with more severe injuries such as subdural haematoma (177) or diffuse axonal injury (178). Therefore, Scher et al. (121) concluded that the risk of severe brain injury was low for impacts from the range of EFH tested.

SUMMARY

Head injuries in skiing and snowboarding comprise up to 38% of all injuries, with concussion comprising a substantial portion of all head injuries. Although head injury is responsible for approximately half of all traumatic fatalities occurring on the slopes, fatal injuries are rare with less than 1% of all skiing head injuries ending in death.

Head injuries typically occur to males aged 23 to 29 years with novice or intermediate level alpine sport skills on mild to moderate slopes. Skiers typically fall forwards impacting the frontal region of the head, whereas snowboarders typically fall backwards impacting the occipital region of the head. Other common head injury situational events involve colliding with objects or other people when skiing and crashing on jumps in terrain parks when snowboarding. Skiers tend to travel faster than snowboarders at speeds of up to 30 and 22 m/s, respectively. In addition, skiers and snowboarders of higher skill levels tend to travel faster compared to lower skill levels. Some studies have suggested that the impact speed of alpine sport helmet testing standards be increased; however, the travelling speed of a skier or snowboarder is tangential to the slope. As the speed of a skier or snowboarder increases, the impact vector becomes more oblique; however, the normal component remains unchanged. Alpine sports helmet standards require linear drops onto rigid anvils, but the correlation between helmet impacts onto rigid anvils and snow surfaces is unknown. No alpine sport helmet requires an oblique impact test. The presence of a helmet was associated with a significant decrease in peak linear head form accelerations for both skier-to-pole and skier-to-skier impacts. Significant protective effects have been found for skier-to-pole impacts, skier-to-skier impacts and fall impacts to hard snow, but not for soft snow. During landing after completing a jump, the lower limb structure significantly attenuates the impact acceleration. In addition, jump design can affect the execution of a jump and equivalent fall height can be related to head injury risk.

Helmets have long been thought to reduce the risk of head injuries in skiing and snowboarding; however, recent studies have reported inconsistent evidence regarding the protective effect of helmets in alpine sports. Performance standards of helmets used in alpine sports should more closely reflect the boundary conditions of head impacts to skiers and snowboarders associated with injury. For example, a ski helmet standard may include a more severe oblique test to the front of the helmet, whereas a snowboard helmet standard may include a drop test onto the occipital region. Administrative controls are also methods of injury risk reduction, which may include skill training, separating novice from advanced skiers and snowboarders and/or policy regarding passing another person on the slopes. Lastly, engineering controls may be more effective than both protective equipment and education in terms of injury risk reduction (179). For alpine sports, engineering controls include slope design (e.g. gradient, grooming, placement and padding of poles, tree removal) and terrain park design (type, placement and size of features, jump geometry).

CONFLICT OF INTERESTS

McIntosh provides expert witness services, but declares no conflict of interest regarding this paper, its preparation and expert witness services (180).

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Tendon Injuries in the Hands in Rock Climbers: Epidemiology, Anatomy, Biomechanics and Treatment - An Update

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SUMMARY

Background. Over the last decade, rock climbing has become an increasingly popular sport. With the latest inclusion into the Olympic program, this trend will continue upward. Lately, specific tendon injuries on the hand (e.g. lumbricalis tendon injuries or tenosynovitis) are reported to be on the rise within climbing patients.

Design. Clinical cohort study and comparison with literature data. Review of current therapeutic concepts.

Methods. Tendon injuries to the hands of rock climbers were identified from our climbers patient database over the years of 2017/18. These were compared to the numbers of 2009-2012 and 1998-2001. The injuries were analyzed, and the results were compared with the current literature.

Results. Within the ten most frequent injuries over the years 2017 and 2018, three were to the tendons and tendon sheath/pulleys. In a longitudinal comparison of patients in a climbing-specific sports medical clinic, the pulley injury is consistently the most frequent injury, followed by tenosynovitis and capsulitis of the finger joints.

Conclusions. In rock climbers, tendon injuries of the hand are frequent and many of these specific to the sport. Special knowledge about their pathology, diagnostics and treatment is necessary as some of these injuries rarely occur in non-climbing patients. With the further advent of climbing, an increase in injury incidence is to be expected.

KEY WORDS

Sport climbing; pulley injury; tenosynovitis; lumbrical tear; pulley tear; finger injury

INTRODUCTION

Over the last decade, indoor rock climbing has become an increasingly popular sport world-wide (1-3). With the latest inclusion in the Olympic program (Tokyo 2020), this trend will most likely continue (4). The outdoor rock climbing grades are also pushed even further and big rock faces such as "El Capitan" (Yosemite Valley, US) are even getting climbed free solo. With further increases in the popularity of competitive sport climbing, an increase in injury rate and severity may be expected (2, 5). While the most frequent acute injuries in rock climbing (especially bouldering) are ankle strains and fractures (1-3, 6, 7), most chronic injuries affect the upper extremity- predominantly the hand (3, 7-11). These injuries require specific attention as they are unique to this group of athletes (12). Lately, specific tendon injuries (e.g. lumbricalis tendon injuries (13) or tenosynovitis (4, 14, 15)) are reported to be on the rise while other injuries to the tendons of the hand, pulley and tendon sheath, such as pulley ruptures or tenosynovitis are constantly the most frequent chronic injuries in rock climbing athletes (3, 6, 8, 15-17). Secondary injuries also occur in the hand, such as fractures of the hamate hook, based on the high forces applied to the finger flexor tendons (18). The following article focuses on the epidemiology as well as the differential diagnosis and treatment of tendon injuries of the hand in rock climbers. While for the epidemiology our climbing specific database was used as the primary source, the diagnostic and treatment criteria will be described as a review of the current literature.

METHODS

Based on our continuously ongoing database of rock climbing injuries seen and treated in our sports medical clinic, we identified climbers with hand tendon injuries during 2017-2018. These were to be compared to the numbers of 2009-2012 (19) and 1998-2001 (12). After identifying these patients, our treatment files of the injuries were analyzed, and the results of our findings were to be compared with the current literature. Therefore, a comprehensive search of the literature was conducted using the MEDLINE/PubMed and Cochrane databases. The search was performed in March 2019 without date limits to identify studies that reported on specific injuries to the tendons in the hand in rock climbers. Different combinations of the terms, finger injuries, climbing injuries, tendon injuries, rock climbing, sport climbing, hand injuries and bouldering were used. We included experimental and original papers, systematic and non-systematic reviews, case-reports, and book chapters, independent of their level of evidence. Reference lists from the included articles were also reviewed by hand. The identified papers were first screened and then analyzed for which ones focused specifically on hand tendon injuries in rock climbers.

RESULTS

The current literature presents only two sets of analyses of similar patient groups. Nelson et al. (1) analysed climbing injuries treated in American hospitals or emergency rooms from 1990 to 2007 using the NEISS database. They reported that the majority of acute injuries were to the lower extremity, primarily the ankles. Meanwhile, overexertion injuries were more likely to occur to the upper extremities. In a recent analysis, based on the same NEISS database approach, Buzzacott et al. (2) looked into the consecutive years of 2008 to 2016. They also reported that the most frequently injured body parts were the lower extremities (47%), followed by upper extremities (25%). Unfortunately, finger and hand injuries were not further evaluated in these studies. Thus, these analyses of 25 years of climbing injuries fail to show trends in hand injuries. The other series of comparable published climbing patient cohorts are our analyses of climbing patients, seen in our sports medicine clinic.

From 1998 to 2001, we evaluated 604 climbing injuries (20) and from 2009 to 2012, 911 climbing injuries (15). For the actual evaluation, we analyzed the data of 2017 – 2018, to evaluate possible new trends after climbing´s inclusion into the Olympics. This longitudinal comparison of patients in a climbing specific Sports Medical clinic consistently shows the pulley injury as the most frequent injury, followed by tenosynovitis and capsulitis of the finger joints (**table I**). Shoulder and knee injuries are on the rise, while epicondylitis is declining. Also, lumbrical muscle injuries are among the 10 most common diagnoses of climbing patients. It needs to be stated that these three analyses do have a selection bias, as they do not represent a cross-section of all climbing injuries, but a cross-section of climbing-specific injuries which are treated by a specialized center (15). While traumatic injuries (e.g. an ankle fracture) are likely treated by the closest trauma center available, patients with pulley ruptures or other finger injuries are more likely to seek a second opinion in our clinic (15). Within the finger injuries (**table II**), epiphyseal injuries are also on the rise. Injuries to the flexor tendons and their pulley / tendon sheath (pulley injuries, tenosynovitis) make the 2 most frequent finger injuries.

DISCUSSION

Anatomy and Biomechanics

The flexor- and extensor tendons must be looked at separately in anatomical regards, even though the tendons of e.g., the lumbricalis muscles take an exceptional position (8).

The extensor tendons

The long fingers have four common extensor tendons as well as two tendons which are dedicated to a single finger – extensor indices for the 2nd digit and extensor digiti minimi for the 5th digit. The tendon of the extensor digiti minimi runs through the 5th tendon compartment, while

Table I. The 10 most frequent climbing injuries – epidemiological development over 20 years (15, 20).

Injuries 2017-2018 (n = 582)	n	%	Injuries 2009-2012 (n = 911)	n	%	Injuries 1998-2001 (n = 604)	n	%
Pulley injury	72	12,4	Pulley injury	140	15,4	Pulley injury	122	20,2
Tenosynovitis	68	11,7	Capsulitis	87	9,5	Epicondylitis	51	8,4
Capsulitis	54	8,3	Tenosynovitis	80	8,8	Tenosynovitis	42	7,0
Knee injury	42	7,2	SLAP tear	51	5,6	Strain finger joint capsule	37	6,1
SLAP tear	37	6,4	Epicondylitis	50	5,5	Skin abrasions	34	5,6
Impingement (shoulder)	34	5,8	Impingement (shoulder)	40	4,4	Back problems	24	4,0
Wrist strain	34	5,8	Strain finger flexor tendon	36	4,0	Knee injuries	14	2,3
Epicondylitis	21	3,6	Dupuytren disease	30	3,3	Fractures	14	2,3
Spinal injuries	18	3,1	Strain finger joint capsule	25	2,7	Capsulitis	13	2,2
Lumbrical muscle tear	12	2,1	Ganglion finger flexor tendon	19	2,1	Ganglion finger flexor tendon	11	1,8

Table II. The 10 most frequent finger injuries 2017-2018 (n=251), 2009–2012 (n=474) and 1998–2001 (247) (15, 20).

	2017 - 2018			2009 – 2012			1998 - 2001	
Finger injuries (n=251)			Finger injuries (n=474)	n	%*	Finger injuries (n=247)	n	%*
Pulley injury	78	31.1	Pulley injury	140	29.5	Pulley injury	122	49.4
Tenosynovitis flexor tendon	69	27.5	Capsulitis	87	18.4	Tenosynovitis	42	17.0
Capsulitis	49	19.5	Tenosynovitis flexor tendon	80	16.9	Strain finger joint capsule	37	15.0
Epiphyseal fracture	19	7.6	Strain flexor tendon	36	7.6	Capsulitis	13	5.3
Lumbrical tear / strain	12	4.8	Strain finger joint capsule	25	5.3	Ganglion	11	4.5
Strain finger joint capsule	10	4.0	Ganglion finger flexor tendon	19	4.0	Strain flexor tendon	7	2.8
Osteoarthritis	4	1.6	Lumbrical tear / strain	19	4.0	Fracture	7	2.8
Strain finger joint capsule	4	1.6	Collateral ligament injury	17	3.6	Osteoarthritis	7	2.8
Ganglion	3	1.2	Epiphyseal fracture	16	3.4	Soft tissue injury	5	2.0
Contusion	3	1.2	Osteoarthritis	14	3.0	Tendon rupture	4	1.6

all other tendons run through the 4th compartment (8). On the level of the dorsum of the hand and the metacarpophalangeal joints, there are many cross-connections known as the connexi intertendinei. At the proximal interphalangeal joint (PIP) the extensor tendons separate into two lateral reins and one central rein (tractus intermedius). Together, these tendons form the so-called extrinsic system- tendons of muscles which originate proximal of the hand itself (8). The extrinsic system is supported by the intrinsic system, muscles originated within in the hand, the mm. lumbricales, the mm. interossei and the thenar and hypothenar muscles (8).

The flexor tendons and their functional system with the pulley and tendon sheath

Both flexor tendons of the long fingers, the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS), run through the carpal tunnel and pulleys and intersect at the chiasm (8). The thumb flexor tendon (flexor pollicis longus) runs through the carpal tunnel on the radial aspect of the forearm and is strengthened by two pulleys. The muscle passes through an osteofibrous channel to the base of the distal phalanx (8).

The annular ligaments and the cruciate ligaments are seen as a reinforcement system of the flexor tendons along the osteofibrous channels of the fingers and are fixed to the phalanges (21). Five annular (A1-A5) and 3 weaker cruciate ligaments (C1-C3) are to be distinguished (21, 22) (**figure 1**). Pattern and arrangement of these ligaments vary (22, 23). All pulleys have different functions in stabilizing the flexor tendons at the palmar sides of the phalanges (22, 24-26). The main function of the flexor tendon pulley system is to hold the flexor tendons close to the bone, thus converting linear force into torque resulting in rotation at the interphalangeal (IP) and metacarpophalangaeal (MCP) joints (27). The A2 annular ligament plays the most important role in guidance of the flexor tendons, (28-31). A minor role in force transmission and tendon deflection is performed by the A1 and A5 pulleys (27). The pulley system suppresses the tendon excursion, and the force of the flexor tendons is transferred efficiently in flexion and hyperextension to reach the full range of motion (27). The lumbricalis and interossei are exceptions, as they originate from the flexor tendons themselves and end in the tendinous hood of the extensor tendons (13). Their function is flexion in the MCP and extension in the proximal (PIP) and distal interphalangeal joint (DIP) (8, 13, 32).

Blood supply of the flexor tendons is guaranteed through the “vinculae tendinae” in the region of the osseous insertion of the tendon as well as in the osteofibrous channel (8, 13, 32). Venous drainage is performed through the same system (8). Verdan (33) subsequently divided the flexor and extensor tendons into different regions of interest regarding injuries, prognosis and nutrition (34).

A differentiation between the thumb and the index finger is also necessary. The flexor tendon of the thumb (flexor pollicis longus) runs through the carpal tunnel on the radial side of the forearm, and strengthened by 2 pulleys, the muscle passes through an osteofibrous channel to the basis of the distal phalanx (8).

Injury patterns

Injury patterns are differentiated into open or closed, sharp or blunt, traumatic or degenerative lesions, as well as injury to the dorsal or palmar surface (8). Open injuries to the tendons in rock climbing are rare (8, 12, 15) and only happen due to a direct trauma to the skin and underlying tendons. These may result in ruptured tendons or more seriously in finger avulsion amputations, due to the rope performing a loop and the respective finger getting caught within it while the rope tensions in a fall (12, 35, 36). Another possible injury mechanism is a finger getting stuck in a finger pocket and excessively bending, leading to an open injury or a blunt tendon disruption (37). Closed injuries are more frequent in climbers and most often occur acutely to the finger flexor tendon pulleys or as a chronic injury to the

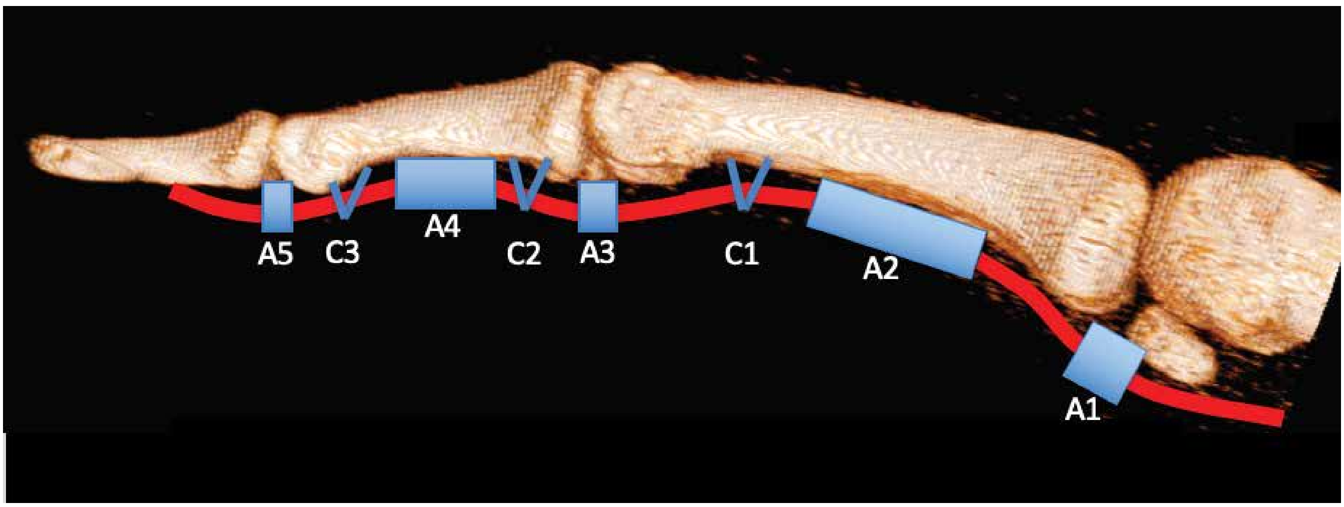

Figure 1. The pulley system of the finger flexor tendons.

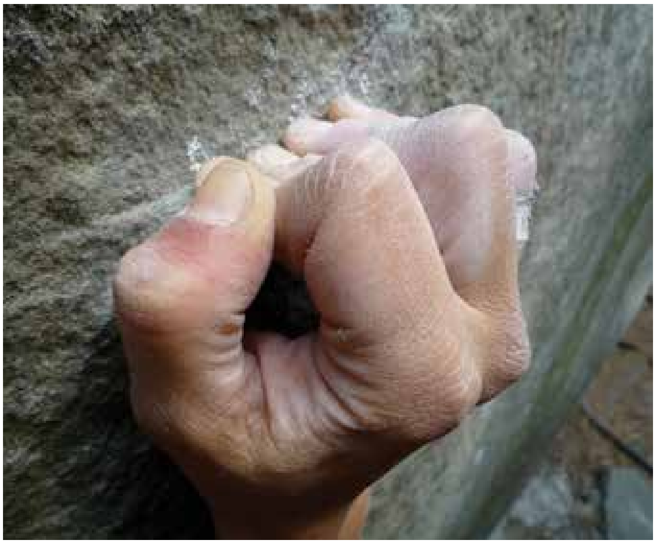

Figure 2. The crimp grip position.

Figure 3. The hanging (sloper) finger position.

tendon sheath (12). Various climbing holds can lead to various corresponding injuries (21, 24, 25, 27). The crimp grip position (**figure 2**) is well known to place high forces on the flexor tendon pulleys (21, 24, 25, 27). In addition, the eccentric movement of the fingers while climbing along with the and the friction beneath the pulleys, play a major role (24, 28, 38). The hanging (sloper) finger position (**figure 3**) is more likely to cause flexor tendon strains and tears (12).
Tendon avulsions, first mentioned by von Zander (39) in 1989, mostly affect the insertion of the FDP-tendon at the distal phalanx (8). Usually, this injury is seen on the 4th finger, as the FDP-tendon is embedded inbetween the double-sided lumbrical tendons, as shown by Manske and Lesker (40) in cadaver dissection (8). We were able to verify this injury, especially in rock climbers, based on chronic degenerative damages to the tendon (13, 32).

Diagnosis

In clinical examinations of lacerations, one has to remember that even small cuts can cause severe damage underneath the surface. For example, a partial rupture of 90% of the tendon can seem to be functionally intact yet can then rupture secondarily after considerably minor stress (8, 41). The function of the FDS and FDP tendons needs to be examined separately. A pulley lesion may become apparent with a bowstring-phenomenon (42). In addition to the clinical examination, ultrasound and MRI are well-established tools to detect closed tendon injuries, as well as to assess injuries to the pulleys and tendon sheaths (12, 21, 43-49). Ultrasound is performed in a supine position with longitudinal and transversal planes, using a linear transducer (13-18 MHz). For signal enhancement, a gel standoff pad is used or the examination is done in a warm water basin. Only in rare cases will an additional MRI (or CT) need to be performed (21, 42, 47). A considerable advantage of the ultrasound is the possibility of dynamic examination, which can demonstrate tendon excursions through "forced flexion" better than a static method (48, 50, 51). Additionally, inflammatory processes can easily be demonstrated (effusion, increased blood flow) and cellulitis, ganglion cysts, bone marrow edema and phlegmonia can be better visualized and detected (46, 49, 52). Diagnosis of a pulley lesion is performed in forced flexion of the finger, meaning active pressure of the finger towards the transducer (21, 53). Thereby, quantifications of the enhanced distance between bone and flexor tendon, as seen in pulley ruptures, can be made (21, 53). A recent cadaver study showed that injuries to the A2 and A4 pulleys could be diagnosed via ultrasound with sensitivities of 90% and 94%, and specificities of 100% and 97%, respectively (45). An increased tendon-bone distance of more than 2 mm in forced flexion is the general diagnostic criteria for a rupture (45). This cadaver study also proved the technique's capability in the diagnosis of A3 pulley injuries, using an increased distance of more than 0.09mm between the flexor tendons and the volar plate (45). If the ultrasound fails to lead to a conclusion, an additional MRI should be performed. Using the MRI, a more specific differentiation of inflammatory processes or posttraumatic osseous edema can be made (48, 52). More recently, dynamic MRI techniques are becoming available (43, 44, 54).

Differential diagnosis and treatment

In the following section, the respective injuries and their essential therapeutic approach are presented. Nevertheless, focus is kept on the most frequent and climbing specific injuries.

Pulley injuries

As already stated, injuries to the finger flexor pulley system are the most common finger injury in rock climbers (15). Caused mainly through the crimping position (**figure 2**) the A2, A3 or A4 pulleys, which are considered the most important ones for this type of activity and prone to the highest stress level, can either be strained or ruptured (21). Usually only one of the finger flexor tendon pulleys disrupts-the A2 or the A4 pulley (37). Singular c-pulley ruptures rarely happen (55). A pulley injury in rock climbers was first described by Bollen and Tropet in 1990 (56, 57). Nowadays, closed pulley injuries are also reported in non-climbing patients (58).
The diagnosis of a pulley disruption is based on the history (pop or snapping sound) and the clinical examination, where a painful flexor tendon bowstringing can be palpated during resisted finger-flexion. The lift-off or bowstringing of the tendon is visualized by ultrasonography (50) or magnetic resonance imaging (48, 59). Single pulley-disruption are treated conservatively since Schöffl et al. (60) showed that also with non-operative management, no objective or subjective functional loss occurred (3, 21, 37). The healing-time of the pulley is between 2 and 3 months and full load-bearing can be expected after 4-6 months (21, 37, 61). An injury involving multiple pulleys should receive a surgical repair as they otherwise lead to flexion contracture (21, 62, 63).

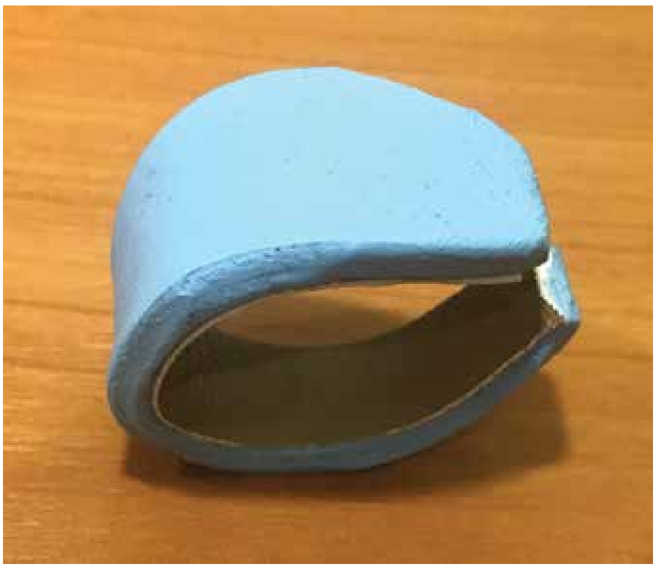

Figure 4. Pulley protection ring.

For the conservative therapy, the use of a special pulley protection ring, which is formed in a way that the neuro-vascular bundles of the finger are out of compression, allowing an adequate reposition of the tendon without compromising circulation within the finger, is implemented for two months, followed by a pulley protection tape (37, 61) (**figure 4**). With this treatment regimen, Schneeberger and Schweizer (61) were able to reduce the initial bowstringing at the A2-pulley by 50% and at the A4-pulley by 40%. If, however, two or more pulleys are disrupted, the amount of bowstringing increases substantially, leading to a loss of active flexion range of motion of the finger and a surgical pulley reconstruction has to be considered (37, 60). The results of such interventions are generally good and do not differ considerably between different surgical techniques (64, 65). Recently, the encircling techniques as an alternative approach showed the disadvantage of occasional bone loss (66, 67) and a transosseous modification was presented (62). . However, whether all these patients need a reconstruction at all is still being debated (37). We have seen a series of patients with multiple pulley ruptures who returned to their previous climbing level without restriction except for a small loss of flexion range of motion (37). This concept only works if there is no clinical bowstringing or early onset of contracture. The pulley support ring therapy must be started within a few days after the trauma and be performed strictly for 6 to 8 weeks. Overall, the general approach in multiple pulley injuries is still surgical. It also needs to be considered that pulley reconstruction leads to a rehabilitation time of several months.
Some concepts for prevention of pulley injuries exist. A general protective pulley-tape around an intact pulley is very unlikely to be effective in healthy fingers (68, 69) and showed evidence of even increasing injury risk (70). The main positive effect is that the PIP joint is not flexed more than 80-90° if the tape is applied close or even over the PIP joint itself (37). More important is the correct warming-up procedure and the avoidance of a pronounced crimp grip position. It has been shown that over the first 120 climbing moves, the amount of physiological bowstringing of the flexor tendons shows an increase of up to 30% (37). Therefore, climbing about 3-4 routes with 40 moves or 8-12 boulder-problems with increasing intensity is recommended as a warm up (71). After a pulley injury, tape should be applied at either the distal end of the respective injured pulley (71) or as an H-tape at the level of the PIP joint (72). In some cases, the leftover trunk of the ruptured pulley can cause complications, leading to a tenosynovitis (Flap irritation

phenomenon) (73). **Figure 5** gives an overview of the therapeutic concept (42).

Tenosynovitis

Tenosynovitis (tendonitis, tendovaginitis) is the most important differential diagnosis to the pulley injury and the most frequent overuse syndrome in climbers fingers (20). It is commonly referred to as tendonitis by laypersons and climbers, but is in fact an inflammation of the tendon sheath (12, 74). An inflammatory response occurs after repetitive stress and its onset can either be both acute or chronic. The climber suffers from pain, occasionally accompanied by a minor swelling along the palmar surface of the digit, around the same area as a pulley injury. The pain can extend into the palm or the forearm. Diagnosis can be made through ultrasound which detects a "halo" phenomenon around the tendon (12, 50) (74) (**figure 6**). Increased accumulation of liquid around the tendon is most clearly visible in a transversal plane (53). As climbers tend to have more liquid in their flexor tendon sheets after high stress on various ranges, no clear information can be given about the normal range (12). It is best to compare the ultrasound finding of the injured finger to the same finger on the contra-lateral side (12). The therapy consists of anti-inflammatory medication, resting on a splint for several days, external ointment applications, brush massages (with a toothbrush), ice therapy and, in a persisting condition, local cortisone injections (9, 12). These injections are not always avoidable, as the chronic tenosynovitis can be stubborn (12).

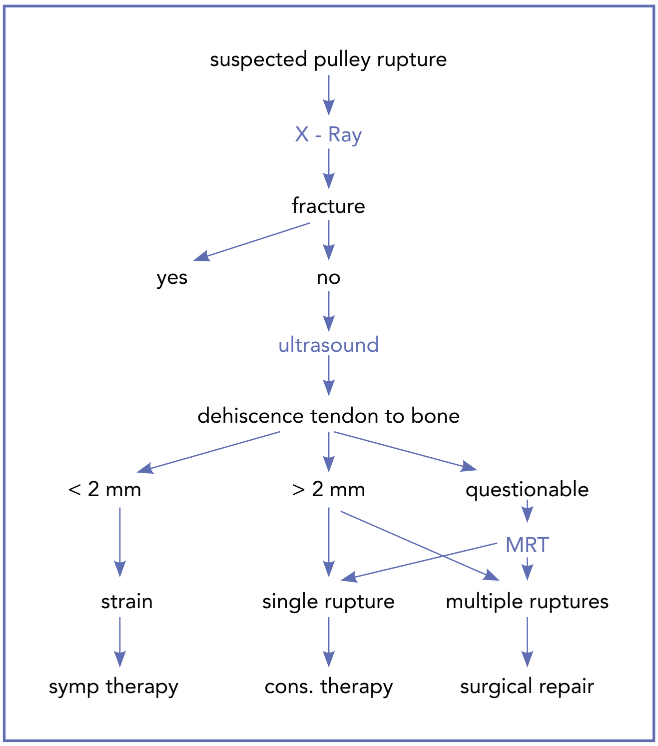

Figure 5. Therapeutic algorithm of pulley ruptures (42).

Tendon strains and ruptures

Directly injured tendons were observed in a few cases, most often caused by a sudden stress on a hand or finger in a hanging position (e.g. the foot slipping off a foothold) (12). Patients present with pain running along the course of the flexor tendon (35). This pain increases in the hanging position, while sometimes it can be totally gone in a crimp position. Diagnosis can be rather difficult, in which case ultrasound and MRI can be used. In flexor tendon strains, the recovery can be prolonged and the recurrence rate is high. Therapy is conservative combined with therapeutic ultrasound. In rare cases, a partial tear of the tendon occurs which can lead to tendon nodules and triggering (75, 76). Complete tendon tears are rare and require a surgical revision (**figure 7**). As they are mostly based on a degeneration of the tendon, a primary fusion may be advisable if the tear is at the level of the distal interphalangeal joint (12, 32, 35).

Lumbrical Shift Syndrome

Lumbrical shift syndrome is a rather seldom, but very climbing-specific pathology which was first described by Schweizer (77). The incidence of a lumbrical muscle tear is increasing due to the popularity of climbing (13). It is caused by a so-called "quadriga effect", which describes a shear inju-

Figure 6. Halo-phenomen around the flexor tendon in ultrasound of tenosynovitis.

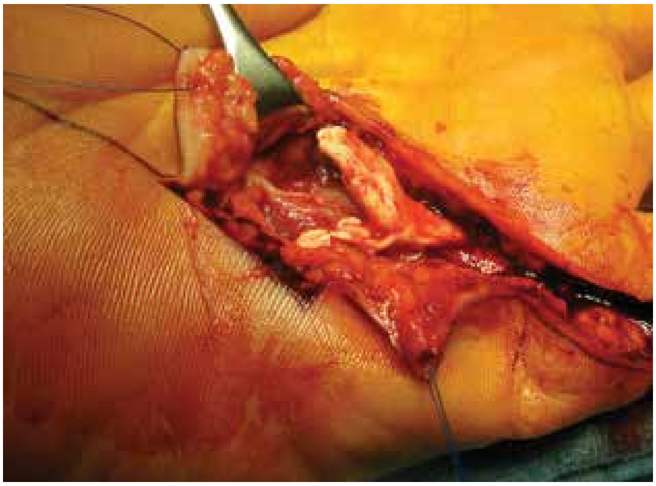

Figure 7. Complete tear of the profundus and superficial flexor tendons of the 5th finger in a climber.

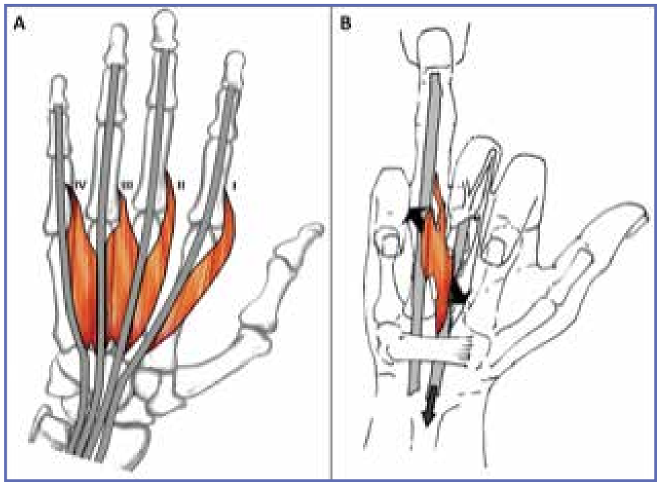

Figure 8. The "quadriga effect" in lumbrical muscle injury (13).

ry resulting from pathologic stress to the two origins of the bipennate lumbrical muscle (13, 78, 79) (**figure 8**). This pathomechanism results from gripping positions of the hand in which one or two fingers are extended, while the neighbouring fingers are actively flexed (78, 79). This increases the maximum strength by up to 50% and causes a shift of the FDP tendons and its common muscle body of the various fingers against each other leading, to muscle strains or partial tears (13, 77). In the clinical examination, pain only becomes obvious if one finger is extended while the others are flexed. If the climber pulls with all fingers in extension, the pain is gone. Therapy consists of symptomatic treatment, taping and carefully stretching of the muscle (38). It is very important to start with stretching exercises immediately, which is done in the same way that the injury was provoked, but with much less load (37). Lutter et al. (13) reviewed data from 60 consecutive patients with a positive lumbrical stress tests which included clinical examination (n=60/60), ultrasound (n=60/60), magnetic resonance imaging (n=12/60) and outcome (n=60/60). Lumbrical muscle tears were graded according to the severity of clinical and imaging findings as grade I-III injuries (13). The therapy consisted of adapted functional therapy (13). 30% of patients had grade I injuries (microtrauma), 53% had grade II injuries (muscle fibre disruption) and 16% had grade III injuries (musculotendinous disruption) (13). All patients had an uncomplicated outcome with complete recovery and unaffected return to climbing (13). The healing period in Grade III injuries was significantly longer than in the two other groups (p<0,001) (13). Based on their study Lutter et al. (13), a diagnostic and therapeutic algorithm is presented in **figure 9**.

Extensor hood syndrome

In athletes with a long history of climbing activity, progressive osteoarthritic changes of the small finger joints have been observed (80-83). These changes can present as large bone spurs on both the flexor and extensor sides of the digits (8, 84). With intensive use of the crimp grip position during climbing, these bone spurs can produce irritation to the extensor tendons (84). Schöffl et al. (84) reported about 13 rock climbers in a 3-year period complaining of dorsal-sided pain of the proximal and/or distal interphalangeal (PIP/DIP) joints. Plain radiographs revealed dorsal bone spurs (osteophytes) on the PIP joint in all climbers and on the DIP joint in three climbers (84). According to the Kellgren-Lawrence scale (85) the radiographs (in 7 cases bilateral) revealed 5 grade 2, 12 grade 3 and 3 grade 4 osteoarthritis. Each of these dorsal bone spurs were causing irritation to the extensor hood, resulting in fluid accumulation and tenosynovitis-like conditions even if the extensor tendons do not have true tendon sheaths, compared to the flexor tendons at the level of the DIP and PIP joints. In two cases, the dorsal osteophyte had already broken off (84). The therapy is primarily conservative with anti-inflammatory ointment dressings or local steroid injections; in rare cases, however, an operative excision of the dorsal sided bone spurs is necessary to release the stress from the extensor tendons (84).

CONCLUSIONS

Tendon injuries of the hand are frequent and sport-specific injuries in rock climbers. Specific knowledge about their

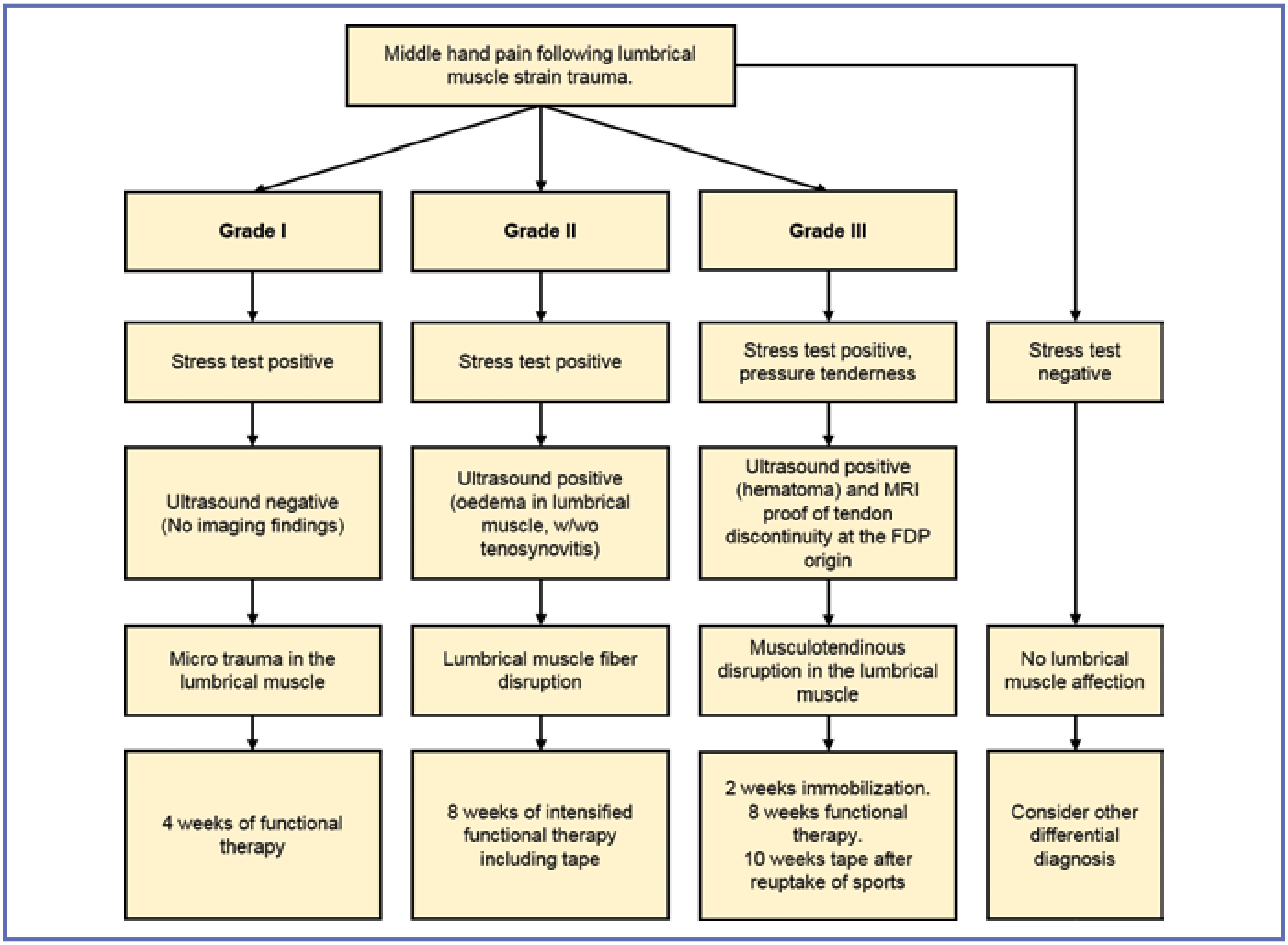

Figure 9. Diagnostic and therapeutic algorithm for lumbrical muscle injuries (13).

pathology as well as diagnostics and treatment is necessary, as some of these injuries only rarely occur in non-climbing patients. With the further advent of climbing, and with the expected further increase in overall training load due to the sports inclusion in the Olympic program, a further increase in injury incidence is expected. Thus further work regarding tendon injury prevention and the possible effects of compensatory training is necessary (70).

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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ORIGINAL ARTICLE

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Assessment of the Ultimate Actual Strength of Rock-Climbing Protection Devices: Extraction Tests in the Field and the Human Capability to Predict the Ultimate Strength

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SUMMARY

Background. Rock climbing protection devices are crucial for climbing practice safety and for mountaineering in general. The use of these devices, together with appropriate techniques, reduces injuries in the critical event of a climber's fall. Although European standards and rules support the manufacturer in the design, production and laboratory testing, a thorough investigation of their behaviour in a real environment and during an actual placement has not yet been performed.

Methods. The aim of this work is to present an insight into the strength of such devices through the application of a monitored, quasi-static, increasing force in a field environment. Results from several types of devices (pitons, nuts and cams) are presented and critically evaluated with respect to the values of the loads acting on the anchors due to the fall of the climber.

Results. As far as the piton actual strength is concerned, the present activities show that the characteristics requested by EN specifications and rules are functional for product qualification purposes, but of very little use when defining the load holding capabilities once the devices are in place. However, even if the actual strength does not match the requirement of the standard, the comparison with the actual load applied is fairly encouraging. With regards to nuts and cams, it is worth underlining the importance of a correct placement: when placed correctly, the actual strength achieved by the device in the field complies and is higher than the classification of the EN standard. Moreover, an investigation of human capability to predict the ultimate strength of rock-climbing protection devices placed in the field has been carried out, with the aim of verifying the reliability of the climber's judgement, and, possibly, improve the safety of the in-field decision-making process.

Conclusions. The lesson learned from the experiments is that modern equipment shows one step better behaviour and, similarly to pitons, the device-rock coupling dictates the pairs actual strength, assuming of course a sound placement. To the author's best knowledge, the present work represents the first attempt to investigate the human capabilities to assess the reliability of a protection placement in-field.

KEY WORDS

Rock-climbing protection, actual strength, human prediction

BACKGROUND

While climbing a long rock or ice route, mountaineers are tied by means of a rope. The climb is subdivided into "pitches" by "stances" (or belay stances), *i.e.*, places where anchoring points are available for security and for the mutual belay of the partners. Focusing on the security task, the anchors are used as 'runners' as the climber, one of the partners, 'lead climbs' higher from one stance to the next one. Note that from now onwards, the terms "anchor" and "protection" will be equivalently used to indicate the safety devices that are placed in the rock to protect the climbers (both for creating a stance and as a 'runners').

When the climber falls in a leading situation, the fall length is approximately twice the distance of the leader to the closest runner; the runner is therefore a constrain of the rope (and the mountaineers) to the rock or ice wall. This scenario can clearly produce severe loading on the anchors, as well as the possibility that the anchors fails, thus reducing the points of attachment of the rope on the rock wall-potentially critical for the safety of the mountaineers. In order to reduce the intrinsic risk of a complete detachment of the rope and mountaineers, the stance is built as a system of multiple anchor points, which are usually interconnected to increase safety. For several reasons, in case of a fall of a climber, the magnitude of the load on the stance is sensibly lower (as described in more detail below), and the multiple anchor system works synergistically in order to avoid catastrophic detachment of all the partners from the wall. A brief description of modern climbing methods can be found in (1). It is worth mentioning that protection devices are supposed to work together with other mountaineering equipment, specifically with an elastic rope that provides a limited reaction force to gradually stop the climber in case of a fall. The formerly UIAA 101 (2), followed by the formerly EN-892 (3) requires a peak force of the rope during testing lower than 12 kN. This is the peak force registered by the rope during a dynamic test in laboratory conditions. This condition is representative of an almost worst case. In the field, several factors reduce the maximum load to a level closer to 5-7 kN, as also discussed in the present article. As far as the stance is considered, a lower load can be considered on the single anchors of about 2-4 kN (4). The aforementioned equipment, including several others not described here, work like a safety chain. The safety chain is a concept developed by the UIAA (and followed by EU standards) to describe and harmonize all the pieces of equipment in climbing (rope, harness, carabiners, protections etc.). Standards provide requirements for all these components of the safety chain, so that they all work together in an integrated way in order to avoid catastrophic consequences in case of a fall.

Several types of rock-climbing protection devices are currently used, such as bolts (adhesive and friction expansion rock anchors), pitons, passive devices (tapers and camming chocks/nuts) and active devices (spring loaded camming devices also known as frictional anchor and called “friends” or “cams” in climber’s jargon). European standards and rules provide design and strength requirements to the manufacturers, but the compliance verification tests are carried out in laboratories and do not consider several important issues: different types of rock (different strengths and different friction coefficients between the rock and the device), different shapes of cracks (where the devices should be placed), the users’ ability of the placement, etc. Several climbing routes, especially modern ones, are equipped with chemically and/or friction bonded rock-climbing anchors called bolts. The strength of these devices is generally orders of magnitude larger than other types of protections (5) and several studies are available as similar anchors are used in civil engineering. These anchors are placed by means of drilling an artificial hole inside the rock, are permanent, and thus are less sensitive to variability due to placements. Some concerns arise for the permanent placement under aggressive environmental conditions (6). However, these conditions are not of interest for the present study. With regards to pitons, passive devices and active devices, their strength is strongly dependent upon the placement in the field. Due to the fact that their use is crucial for climbing practice and for mountaineering safety in general, an insight into the actual strength of such devices is critical in order to reduce injuries in the event of a fall of a climber.

Realistically simulating the force exerted on climbing equipment due to the fall of a lead climber is very difficult to achieve. Consequently, there are not any proven methods within the current literature for verifying the behaviour of rock climbing in such events. A methodology suitable to investigate these issues in a real environment, as well as to measure the strength both in terms of maximum load and failure analyses, could be of great interest in order to critically assess the equipment strength and also the correct procedures for the placement. Correct placement is fundamental in achieving the maximum strength of an anchor when withstanding the load generated during fall.

Although the actual load application is dynamic, the European standards refer to static tests to verify the compliance to the requested strengths. While static *versus* dynamic tests is a point to be discussed, it seems reasonable to neglect the strain rate effect, and the dynamic influence on the behaviour of the devices due to impact velocity is relatively low (although for spring loaded camming devices this subject needs more accurate evaluations for the dynamic behaviour induced by the spring).

In this work we exploit a thorough in-field experimental campaign conducted by a team of expert climbers, some of which also have a structural/mechanical engineering background. This allows to better understand the actual behavior of these devices and, possibly, to highlight how the type of device (material and geometry) and the boundary conditions in which they operate (cracks in rock material) affect their in-field protection capability (*i.e.*, their ultimate strength). The strength of these protection devices was tested through the application of a monitored, quasi-static, increasing force in a field environment.

Moreover, dynamic falling tests were also performed both in laboratory environments and in the field. These tests were only aimed at measuring the load at the level of the anchor, but not the anchor strength (in most of the cases the anchors used in these tests were dummies with a very high strength and therefore had no possibility of failing during the application of the load). These tests involved dropping a weight mimicking a fall of the climber from a given height and measuring the load on the last protection and/or on the stance of the anchor/safety chain.
The load data collected in both types of tests were statistically processed to infer (i) the behaviour of the different protection devices in different operative conditions, and (ii) to estimate a trend of the load that was applied to such devices, to be able to identify the most critical conditions. The proposed statistical framework estimates the probability of device failure based on the conditions of a fall. Results will show that the strength of the anchors depends on the limit value of the anchor, the rock type, and the placement, in combination with a large variety of loading conditions that act upon the anchor.
In addition, experts were polled on their predictions of the failure loads before the trial actually took place. These data were used to investigate how capable experts would be at predicting the strength of rock-climbing protection devices before failure based on the testing conditions. Comparing the objective test results and the subjective expert estimations, the decision-making process can be improved in a real climbing environment. A total of 106 extraction tests were performed and more than 1000 predictions made.

EXPERIMENTAL TESTS: METHODS

Static tests were carried out on pitons, chocks and cam devices placed in a real environment and loaded by means of an oleo-dynamic piston, (**figure 1**). This system can be easily attached to any rock (or ice) surface and is able to apply a parallel-to-wall load by means of a common actuator. A gauged uniaxial load cell (50 KN rated) was used and the peak value was recorded (blue box, **figure 1**). The load cell was placed between the cylinder and the anchor, recording the collapse load. The anchor is shown inside the red circle in **figure 1**. Care was taken to avoid tangential strain to the cell. The hydraulic piston was fixed with a chain and pulley system to allow free movement of the piston alignment on the loading action line. The load application rate was set at a few mm/s and took roughly 10-20 seconds for the complete collapse. The cylinder was controlled by an oleo-dynamic system fed by a pump driven both electrically and manually. The tests were conducted on several types of rock walls, including both hard rock (porphyry and granite) and soft rock (sandstone and dolomite). Bedogni and Manes, used a similar device for the assessment of ice screws in the field (7). Hard and soft rock are both typically found in climbing activities, however, different failure modes are expected. The expected failure mode of anchors in hard rock is more often dependent upon the failure of the device, whereas the failure mode in presence of soft stone potentially involves both the failure of the anchor system and the rock itself. The loading mechanism imposed by the piston is "displacement dependent" (in actual falls it is "load dependent"), therefore a temporary load decrease is possible to some extent.
An advantage of using a quasi-static system is that is makes it possible to ensure a system failure with every test. When a dynamic test is applied, the force is driven by the fall event

Figure 1. Extraction tests: the oleo-dynamic piston in the green box, a gauged uniaxial load cell (50 KN rated) in the blue box, the specimen placed inside the red circle.

and it is possible that the safety restraint does not fail. Additionally, albeit the drop test reproduces more realistically an actual fall, dynamic tests present multiple logistical difficulties. Vogwell and Minguez (1) carried out drop tests in a laboratory environment placing anchor nuts in a standard simulated crevice device. Nevertheless, they had to use a standard tensile testing machine in order to determine the ultimate failure load of the anchor because the drop tests failed to break the system.

Tests consisted of a first phase devoted to the placement of the anchors in the field and a second phase of load application. It is essential that the anchor is properly fit to a rock crevice for optimal testing, as the results are dependent upon device placement. Devices were placed by mountaineering instructors and/or mountaineering military corps members: to ensure that the anchors were optimally installed.

In addition to the tests described above, each qualified person attending the tests was also required to make an informed prediction of the failure load of each device before testing.

The purpose was to obtain the predictions of the experts in order to investigate human capability to predict the ultimate strength of rock-climbing protection devices placed in the field. Experts were selected among qualified mountaineering instructors inside the Italian Alpine Club (CAI) and the Corps of the "Guardia di Finanza".

Table I shows the appearance of the piton failure load database. In particular, the first three columns report the specific features of each trial, *i.e.*, the device material (only for pitons, column 1: pitons are usually built using soft steel, S, and high carbon hardened steel, H), the piton length (only for pitons, column 2) and the rock type (column 3): hard rock, H (porphyry and granite), and soft rock, S (sandstone and dolomite), while column 4 reports the observed failure load. At the same time, the columns from the sixth of the expert climber's predictions for each trial are shown when available.

DATA ANALYSIS APPROACHES

The first part of the data analysis was aimed at analyzing the behavior of the protection devices placed in field and comparing the failure loads observed for different protection devices (function, geometry and material) in different operative rock material. In order to perform this analysis, we opted to resort to a probabilistic framework, which naturally allows to account for all the uncertainties involved in the protection placement and the measurement processes, as described in the following.

The statistical analysis of the data collected assumes that the *N* measurements available for each observed quantity are realizations of random variables accounting for all the uncertainties involved in the process. The analysis was initially based on the calculation of the empirical density function of these random variables, which approximates the (unknown) underlying probability density function:

$$f^{\wedge}{}_{N}(x) = \frac{1}{N}\sum_{i=1}^{N}\delta(x - x_i)$$

where *N* is the number of measurements, *x* is the generic random variable (*i.e.*, the failure loads or the dynamic load on the last protection), x_i is its i^{th} available realization (measurement) and δ is the Dirac function. Operatively, the empirical density $f^{\wedge}{}_{N}(x)$ can be computed by creating a properly normalized histogram of the available measurements. In this work, histograms of the different loads analyzed were

Table I. Piton failure load database.

Piton material (Hard - Soft)	length (60 - 80)	Rock type (Hard - Soft)	Failure load (kgforce)	Reference	Prediction 1	Prediction 2	Prediction 3	Prediction 4	Prediction 5	Prediction 6
H	70	H	360	11 Val masino 2012	700	500	800	400	450	400
H	70	H	120	12 Val masino 2012	1200	800	1300	900	1000	1500
H	110	H	634	16 Val masino 2012	1200	1000	1000	1200	1050	1000
H	70	H	870	19 Val masino 2012	900	600	800	900	1200	1000
H	30	H	410	20 Val masino 2012	300	200	300	300	150	300
H	80	H	1857	2 Passo Rolle 1	900		950	750	950	1200
S	65	H	927	13 Val masino 2012	900	700	800	800	950	1000
S	50	H	1200	15 Val masino 2012	500	400	700	800	650	350
S	90	H	2227	17 Val masino 2012	400	500	700	800	600	350
S	60	H	100	21 Val masino 2012	300	300	400	200	400	300
S	90	H	567	1 Passo Rolle 1	950	600	750	1800	1200	800
S	110	H	1210	3 Passo Rolle 1	300	1600	850	750	650	450
S	80	H	1147	4 Passo Rolle 1	400	400	390	600	380	400
S	110	H	1723	8 Passo Rolle 1	950	2000	1550	1400	1800	1300
H	80	S	566	1 Passo Rolle 2014	280	400	300	300	250	300
H	60	S	997	4 Passo Rolle 2014	900	800	1000	1100	1500	1100

created by dividing a range of forces between 0 and 2500 Kg force into 20 bins; then, the number of measurements belonging to each bin was divided by the total number of observations *N* and by the width of the bin w_b (i.e., w_b = 125 Kg force). The number of bins was chosen on the basis of a trial and error procedure aimed at finding a trade-off between the statistical significance of the estimates and the number of measurements available. Note that the outcome of this procedure is a function $f\hat{}_N(x)$ known only at 20 given points, *e.g.*, at the bin centers $x_c = \frac{w_b}{2} \cdot c,\ c = 1, \cdots, 20$. Thus, in order to be able to compare the different empirical densities obtained more easily, the discrete functions $f\hat{}_N(x)$ were "smoothed" using kernel density estimator (8):

$$f\hat{}_K(x) = \frac{1}{Nh}\sum_{i=1}^{N} K\left(\frac{x - x_i}{h}\right)$$

where K is a non-negative function called kernel and h>0 is a smoothing parameter, called bandwidth. Several choices for the kernel function are possible: here we restricted our attention to the popular case of K(·)=Φ(·), where Φ(·) is a Standard normal density function. Intuitively, the kernel density method requires that each realization x_i (measurement) available of the random variable *X* to be associated with a Standard Gaussian distribution with a mean equal to the realization x_i itself and a variance equal to 1. The bandwidth *h* allows tuning the smoothness of the resulting kernel density estimator $f\hat{}_N(x)$, as shown in the reference example of **figure 2**.

The second part of the data analysis was focused on the evaluation of the quality of the experts' predictions of the static failure loads, in order to possibly identify common systematic errors and/or misinterpretations affecting the climber's judgement when practicing in the field. Due to the scarcity and sparsity of the available predictions (not all predictors were always present at each experimental session), we chose to compare scatterplots of the average experts' predictions with the observed static failure loads (**table I**). The data points were combined into different scatterplots (according to the protection device typology, geometry and material, the rock type, or combinations thereof) as shown as a reference example in **figure 3**. This Figure also provides an indication of the quality and, possibly, of the potential consequences of the predictions, which change according to the area of the scatterplot where the data-points are located.

RESULTS

Pitons

Pitons are anchor devices that can be placed inside cracks using a hammer. Generally, they are built with a blade (to be insert in the cracks) with a lug on one side for a karabiner to

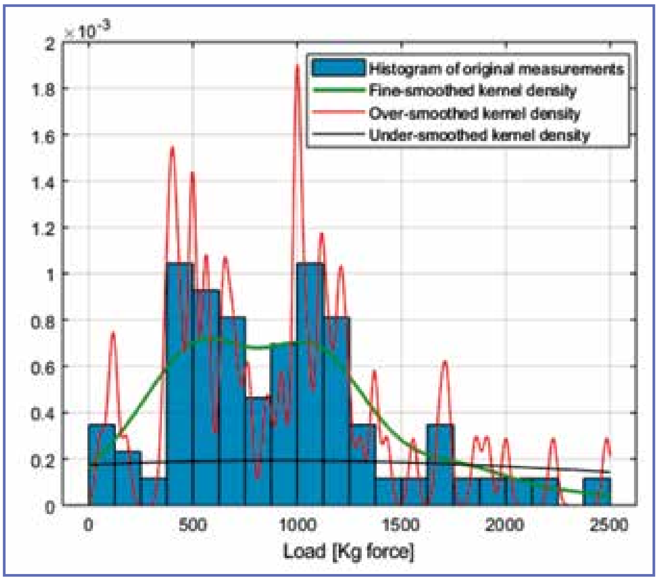

Figure 2. Histogram of the original static failure loads of all the pitons tested during the experimental campaign (light blue columns). Examples of kernel densities with different bandwidths h=20 (red line, over-smoothed), h=200 (green line, well-smoothed) and h=2000 (black line, under-smoothed).

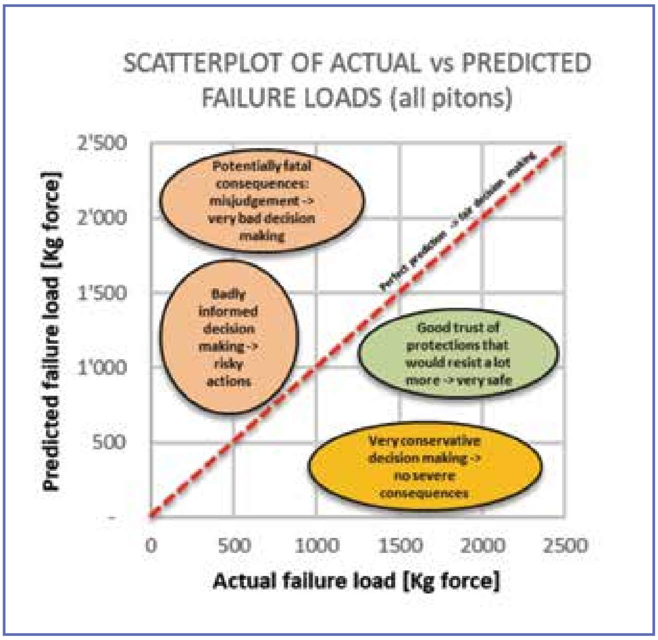

Figure 3. Example of a scatterplot used for categorizing the quality and the potential consequence of in field failure load predictions.

be clipped in. EN 569 (9) requires tensile strength tests with a different loading direction, but with the pitons constrained in an "artificial" holding system. As far as the radial direction is concerned, the minimum values for the ultimate load are 25 kN (for safety pitons, generally used for building stance) and 12.5 kN (for progression pitons). Different configurations and types of pitons were tested. Pitons are usually built using soft steel and high carbon hardened steel. Generally, soft steel pitons should deform inside the crack, making them the common choice for soft rock, whereas hardened steel pitons are usually employed in regular cracks of hard rock such as granite. Both hard steel as well as soft metal alloy types have been tested in soft and hard rock. In order to verify the effect of the material used to manufacture pitons *versus* the type of rock, a variegate campaign of tests was carried out, thus, hard piton/hard rock – soft piton/soft rock – hard piton / soft rock – soft piton / hard rock tests were performed and the results herein exposed.

The most recurrent actual failure mode of pitons is a sort of slippage / pop out of the crack. Thanks to medium speed camera records, the collapse steps were observed: initially, a slight deformation of the piton occurs, followed by a medium-to-severe bearing destruction of the edges of the crack; finally, an abrupt piton pop out concludes the collapse, as shown in Figure 4. The measured ultimate load was scattered from about 6 up to 18 kN. Only in a few cases a mechanical collapse of the piton lug metal part was obtained. This was observed by a failure analysis showing a large permanent deformation of the main blade, and in a few cases, a failure in the section between the blade and the lug, see **figure 4**.

As expected, soft metal alloy pitons exhibit higher plastic deformation whencompared to hard steel. However, soft pitons do not exhibit a lower collapse load, with respect to hard steel ones. The kernel density Figure 5 a) shows that soft pitons seem to offer higher resistance than hard pitons (regardless of their length and the rock type). Mountaineers commonly place hard pitons on hard rock. However, tests show very little difference in the ultimate load; besides, soft metal pitons show an increased capability to deform and to fit the internal shape of the crack also during load application. In the authors' opinion, thanks to the plastic deformation, this type of piton can withstand higher failure loads compared to the hard steel pitons. On the contrary hard steel pitons exhibit a much-reduced plastic deformation making them very suitable for re-use (that could be a key feature in the practical use).

Focusing on other aspects, long pitons exhibit a higher strength than short pitons (provided they are fully hammered into the rock), see **figure 5 b**). A deeper investigation of the differences (in strength) of pitons manufactured with different materials on Granite (hard rock) or Sandstone/Dolomite (soft rock) was carried out. For this purpose, several combinations of piton materials and rock types were tested. A summary of the results is reported in **figure 5 c**) (the results were collected for each type of rock) and are shown in more detail in **figure 5 d**). Ductile metal (soft) pitons placed in hard rock exhibit higher strength, even though this type of combination reduces the possibility to re-use the piton and most likely for this reason, soft pitons are commonly used just in soft rock. Hard metal pitons in hard rocks are likely to perform poorly due to their low capability to adapt. This low ability to deform results in the generation of only a few contact points with the hosting crack and consequently, an abrupt popping out can be expected once loaded. On the contrary, hard metal pitons perform well on soft rock**.**

With reference to the evaluation of the quality of the experts' predictions of the static failure loads, **figure 6** summarizes the outcome of the analysis. More specifically, the scatterplot of all the piton failure loads predicted *versus* the actual failure loads of **figure 6 (a)** shows that, on average, the predictions are quite satisfactory- located in a quite concentrated region around the line indicating the perfect predictions. Interestingly, there is no bias towards either the conservative or the

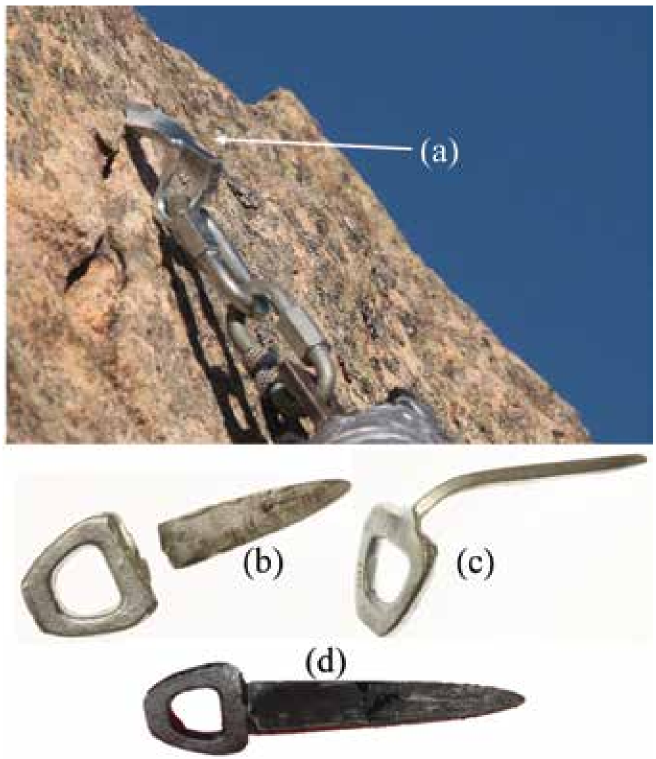

Figure 4. Failure mode of the pitons a) deformed soft piton placed in a crack pops out, b) ruptured soft piton, c) bent soft piton shaft, d) slightly deformed hard piton.

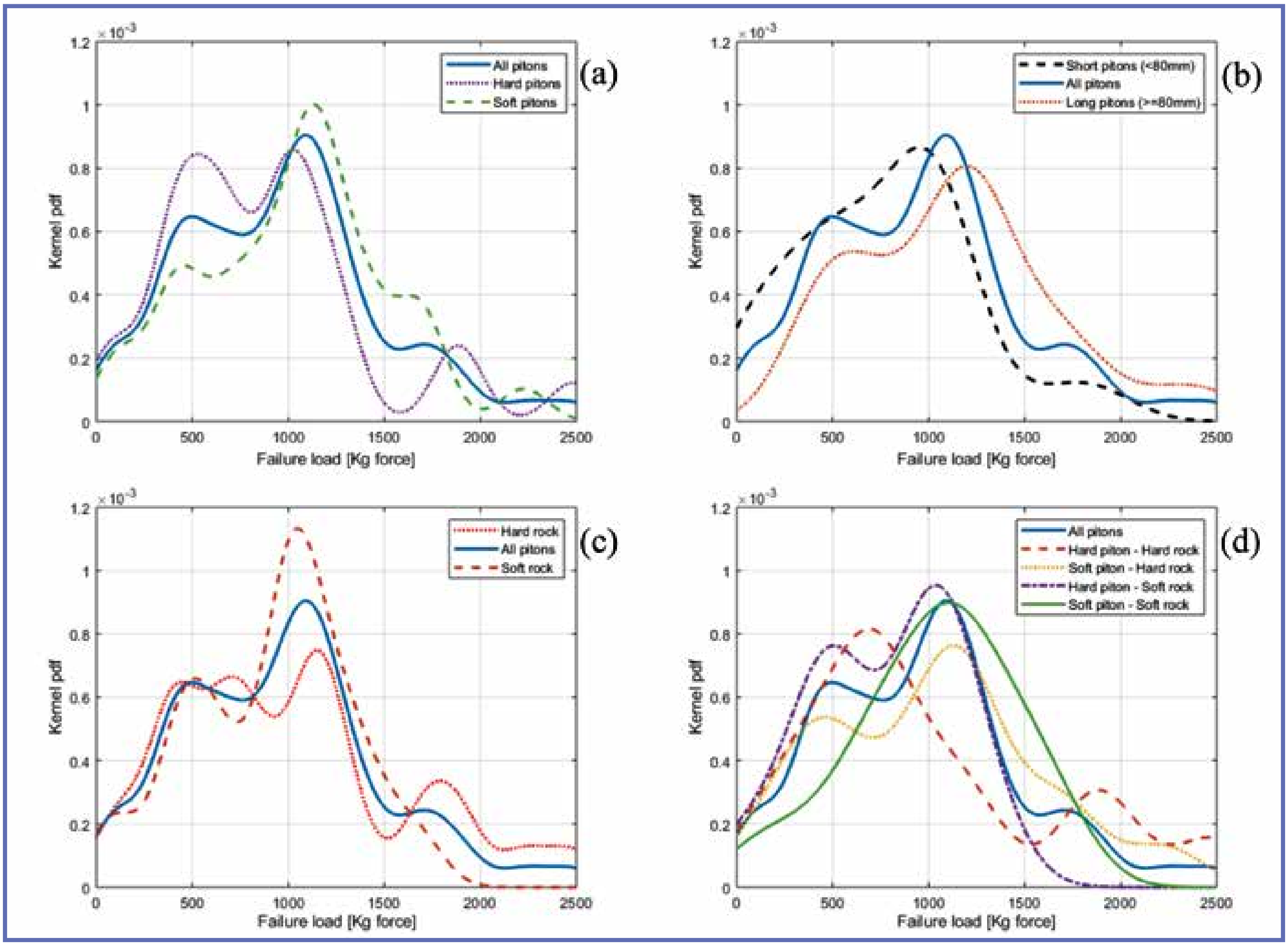

Figure 5. Kernel density of pitons (total of 69 observations available), an explanation of each figure is reported in the text.

non-conservative regions of the plot, but this is probably due to the nature of the experiment, which was testing the predictor's ability without any possible consequences on the predictor him/herself (in that case, much more conservative predictions are to be expected). However, a few outliers can be identified, both in the regions of conservative predictions, and in the region of dangerous predictions, although not in the very non-conservative area. In order to identify the motivations/ causes of these misjudgments, additional scatterplots were created, where only the predictions associated to either a specific piton material (hard and soft, **figures 6 (b)** and **(c)**, respectively) or rock material (hard and soft, **figures 6 (b)** and **(c)**, respectively) are reported. The analysis of these scatterplots shows that the outliers are only present in the predictions involving hard rocks, and not in those involving soft rock. At the same time, the piton material seems not to affect the presence of outliers in the predictions, thus confirming that the experts have more difficulties in predicting the resistance of pitons placed in hard rock or that the mechanical behavior of pitons in hard rock is more uncertain.

Chocks are special shaped nuts attached to a metal wire for placement and the load application by clipping a karabiner. EN 12270 (10) requires that chocks, tested in an "artificial holding" have to prove a failure load over 2 KN. Chocks are simply placed in the crack by hands, so are defined as "fast placement" anchors. All the placed chocks failed without leaving their hoisting crack. Generally, chocks fail at the metal wire, sometimes in the loop interfacing the karabiner body, or alternatively along the wire.

The failure mechanism observed, shown in **figure 7**, consists of practically no relative movement between the chock and the hosting crack, but involves rope loop elongation, initially breaking a single wire, followed by chain-collapse of the

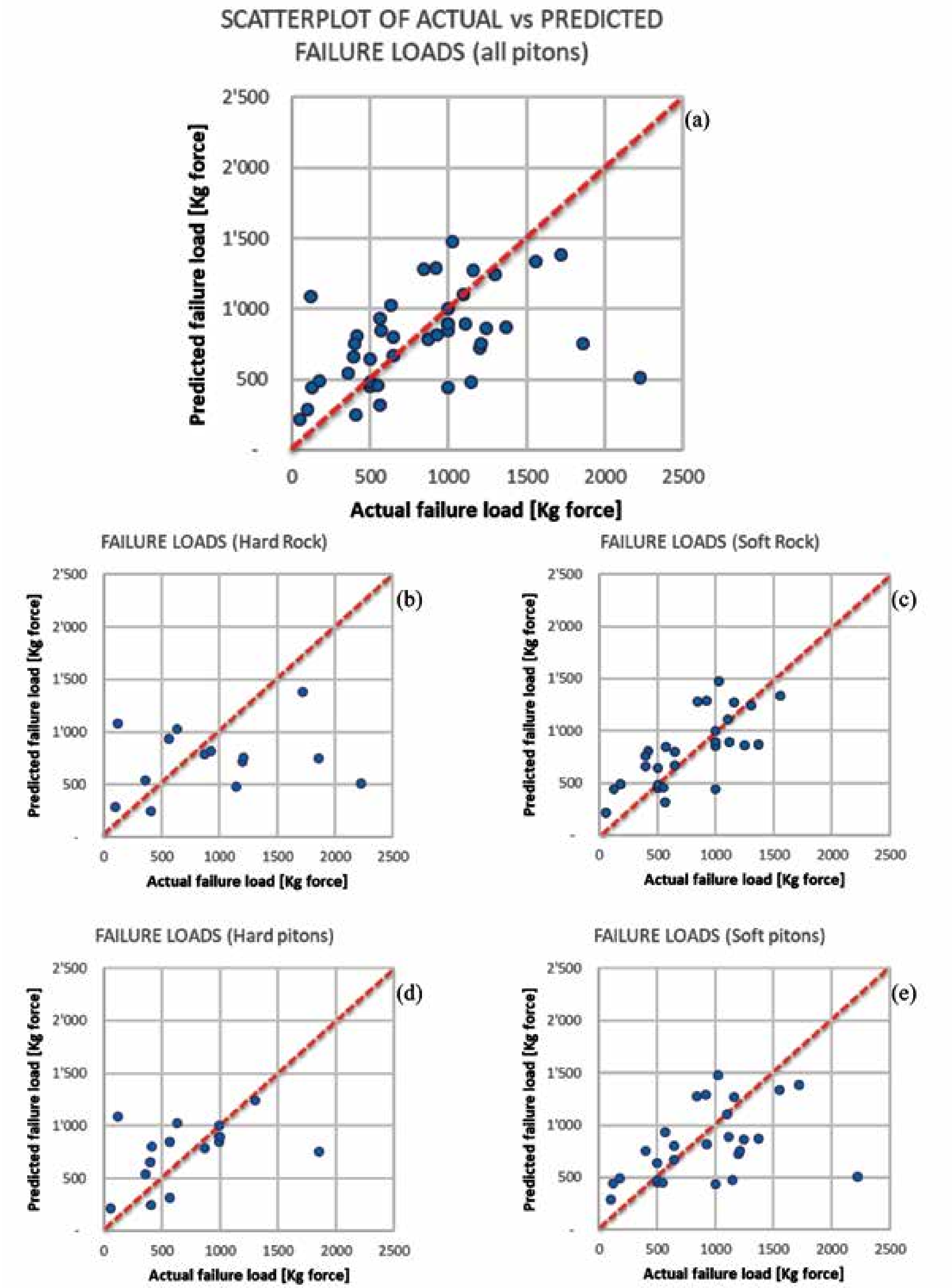

Figure 6. Evaluation of the experts' predictions, an explanation of each figure is reported in the text. Chocks, nuts.

Figure 7. Failure mode of a chock / nut.

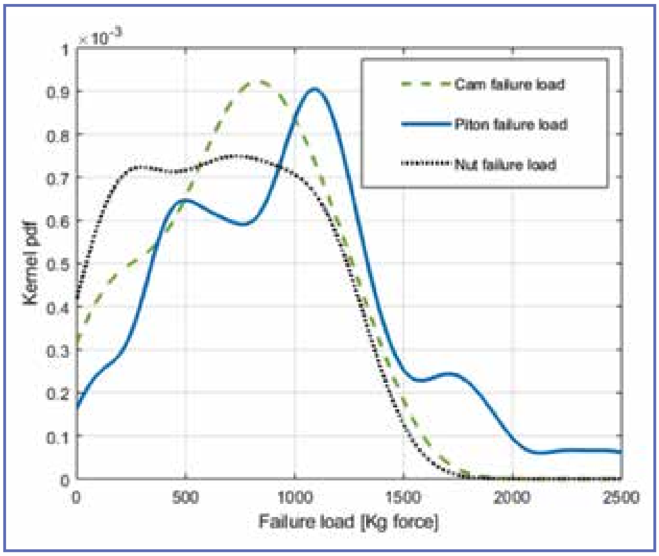

Figure 8. Kernel density of nuts (16 observations available) and cams (21 observations available), compared with pitons (69 observations available).

companion strand wire, up to a full separation, associated to a certain amount with unwinding of a single wire. The "*post-mortem*" analysis proved that chock-to-rock contact points were limited and localized to relatively small surfaces, as witnessed by the chock overall coloured chemical conversion, which remained in pristine condition. The measured ultimate load was scattered between about 6 up to 12 kN, as visible in **figure 8**, thus, higher with respect to the requirement of the standard EN 12270 (10). It is worth mentioning that the spread of the strength is very high, ranging from a high value (close to the pitons strength) to a not negligible number of samples that fail at a very low level of loading. The strength of such a device is, in fact, very dependent on the placement.

The analysis of the experts' predictions by the scatterplot of **figure 9** shows quite good agreement of the predictions with the actual static failure loads. Provided that the number of available observations and corresponding predictions is limited, a slight tendency to conservativeness can be noted for higher failure loads (*i.e.*, probably, better placements), confirming a rather common misbelief of the climbing community that these kinds of passive protection device, when placed in the field, do not appear to be as reliable as they actually are. Indeed, the placement of these protection devices requires great care and much more experience than those required by other safety systems. Moreover, experts are somehow conscious of the level of strength of the device during placement, even if this strength is very reduced (**figure 9** shows just one outlier with respect to this trend). This means that, in a real scenario, users may adopt some action in order to mitigate this possible lower strength, *i.e.* simultaneously placing two or more protections.

Cam devices

Cam devices belong, like chocks, to the group of "fast placement" devices. They are similar to chocks, but due to the incorporated spring system, each device can fit different crack sizes. EN 12276 (11) requires that cam devices (fric-

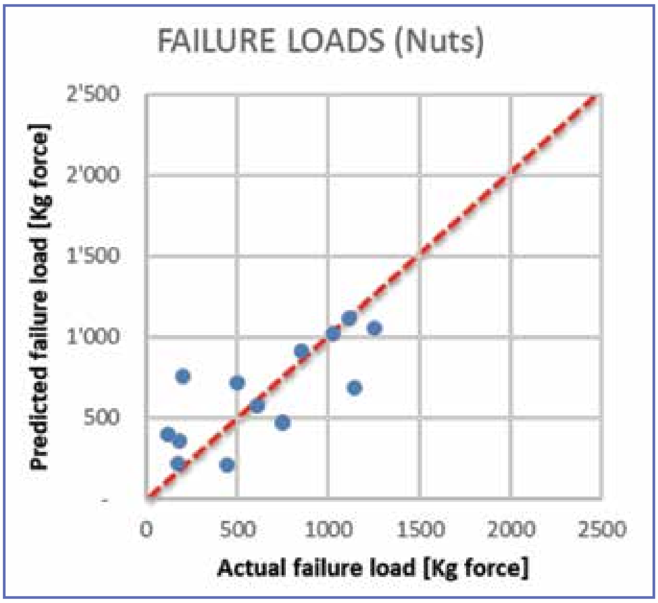

Figure 9. Evaluation of the experts' predictions for the nuts.

tional anchor), tested in an "artificial holding", have to prove a failure load over 5 KN (in two different positions). Due to the fact that their gripping action is obtained by means of friction, different shapes have been designed and built. The devices tested range from: a) old-fashioned solid bar models to b) modern wired body with built-in slings devices, while also testing c) early wired body models. Each of them shows a peculiar failure mode, as shown in **figure 10**. Model a) was characterized by snaking out of the hosting crack exhibiting ultra large permanent bending of the rigid bar or double shearing of the main shaft at both sides of the bar. Model b) popped out from the crack after a snaking settlement as the load increased. Model c) failed in the crimp as the wire loop slide out from it.

From the "*post-mortem*" analysis performed on the failed devices, it was observed that on model b) the only remarkable outcome are the limited scratches on the cam teeth. On the contrary, the other models showed obvious clues of the described failure mode. The measured ultimate load was scattered between 7 up to 14 kN, see Figure 8. Similar to the

Figure 10. Failure mode of the cams.

nuts, the failure load was higher with respect to the requirement of the standard EN 12276 (11).
As for the nuts, the spread of the strength was very high ranging from a higher value (close to the pitons strength) to a not negligible number of samples that failed a very low level of loading; however, very few specimens exhibited a very low strength. Such devices are, in fact, very dependent on the placement, too. Nonetheless, the possibility to adjust the placement by means of a spring that fits different crack sizes make the placement of such a device less critical than the nut placement.
The analysis of the experts' predictions by the scatterplot of **figure 11** shows quite good agreement between the predictions and the actual static failure loads. Contrary to the previous case of the nuts, a tendency to be slightly non-conservative can be observed at low failure loads, which might confirm another common belief to over-trust the performances of cams, even when the placement is not very good (as is the case of low failure loads). Again, it should be noted that the number of observations and corresponding failure load predictions available for the analysis are limited, and further tests should be performed to confirm these behaviours.

ASSESSMENT OF THE STRENGTH VERSUS LOAD

With the aim to verify not only the strength of the protections, but also their capability to withstand the load applied within the safety chain, a further investigation was carried out. As described above, dynamic tests were performed in a laboratory environment and in the field, but in a controlled setup. These tests were carried out separately with respect to the tests on the protections because they are aimed at measuring the actual load on the protection, but not its strength (in most of these tests, the protections used are dummy, characterized by very high strength). These tests involved dropping a weight, mimicking a fall of the climber from a given height and measuring the load on the last protection of the chain and/or on the belay stance. Also, in this case, the observed data was statistically processed by resorting to the kernel density approach. The comparison between the measured loads on the last protection of the chain and belay stance and the ultimate strength of the protections are shown in **figure 12**.
Indeed, safety would recommend strength higher than load, but this is not always possible due to the large spread of the strength, combined with that of the loads. In other words, the uncertainty affecting strength and loads are such that a finite probability exists that the protections fail when dynamically loaded by the fall of a climber. By properly manipulating the data available, it is possible to provide an estimate of this failure probability, *i.e.* the probability *P[Strengths-Loads<0]*. It is important to state that even if the number of tests is considerable, they are not

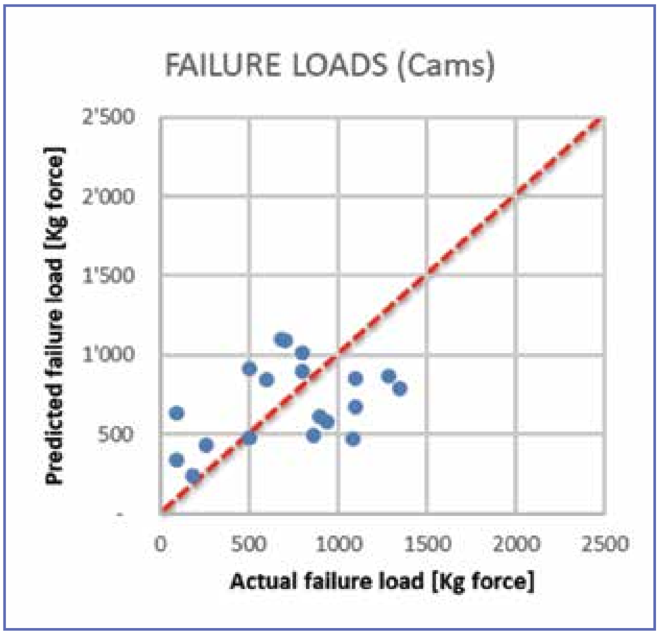

Figure 11. Evaluation of the experts' predictions for the cams.

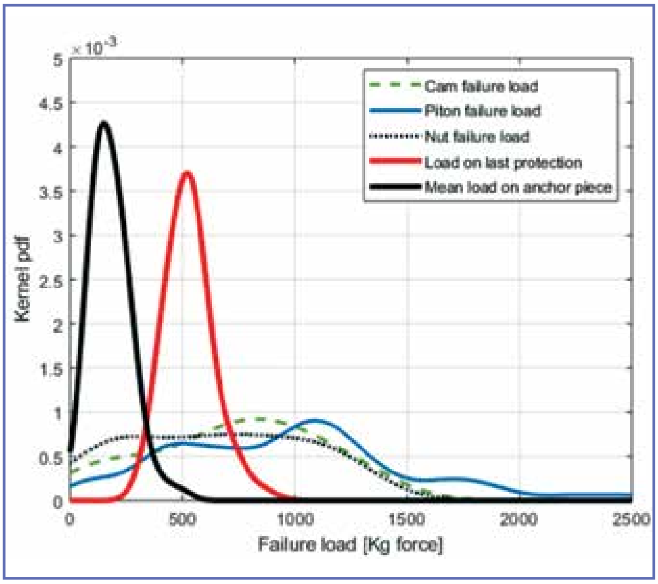

Figure 12. Comparison between kernel densities of strength of the anchors with respect to the kernel densities of the loads applied on the last protection (red, 310 observations available) and on the belay stance (black, 224 observations available).

representative of all the possible cases that occur during actual climbing; in addition, a large spread is present in the data. Thus, the size of the observation population is not always optimal to draw robust conclusions and the statement of the present research has to be considered as an advice for the practice. **Table II** summarizes the results obtained for the different types of protections, considering the possible failure of the last protection of the chain and the failure of the belay stance. As expected, due to the dynamics of the load redistribution among all the elements of the climbing chain, the loads on the belay stance are much smaller than those acting on the last protection, so that the associated failure probability becomes significantly lower. Moreover, it is important to state that it is good practice to build a stance with two or more anchors. Even if the distribution of the load is not uniform on the multiple anchors (4), the load on a single anchor is lower. Therefore, results in **figure 12** and **table II** can be considered as an upper limit for the stance in case the load is reacted by just one anchors-the worst case.
Despite this, the probability of failure of the stance is remarkably low, especially when pitons are used. This is comforting, as a safe belay stance allows a robust constraint of both climbers to the rock or ice wall.

DISCUSSION

Drawing a conclusion was difficult due to the large amount of scattering and the reduced protection population tested. The number of tests (106) and of predictions (approx. 1000) are not low *per se*, but the large variability of the protection types and of its usage make the size of the observation population not always optimal to draw robust conclusions. However, we were able to formulate some remarks.
As far as the piton actual strength is concerned, the knowledge gained through the field experiments confirms that the characteristics requested by EN specifications and rules are functional for product qualification purposes, but of very little use when defining the load holding capabilities once the devices are in place. Spread is remarkable, however, even if the actual strength does not match the requirement of the standard, the comparison with the actual load applied is fairly encouraging. The probability of failure is important when all the type of investigated anchors are involved as the last protection in a fall, but, as expected, it is drastically reduced when they are used for building belay stances. This is especially true for pitons.
As far as the investigation on the effect of the material of the pitons *versus* the material of the rock is concerned, pitons manufactured with ductile steel show a better behaviour in terms of strength, even if they have limited possibility to be re-used, which is clearly a drawback in the mountaineering practice. On the contrary, hard metal in hard rockscan sometimes produce poor performances because of its low capability to adapt; hard metal can generate only a few contact points with the hosting crack and consequently, an abrupt popping out is to be expected once loaded.
With regards to nuts, it is worth underlining the importance of a correct placement: when placed correctly, the actual strength achieved by the device in the field complies and is higher than the classification of the EN standard. This is fairly true in all the arrangements where the “obstacle” function is fulfilled; conversely, lower performance may be expected when the “friction” function (between the wedge-shaped block and the hosting crack) plays a predominant role. The cracks used were very suitable for nut placements, as confirmed by the high value of the failure load predicted by the evaluators. Similar behaviour was observed for cams. In this case better results were achieved with newly designed equipment: this suggests that outdated models should be retired from daily use by their owners.
The lesson learned from the experiments is that modern equipment (cams and pitons) shows a “fit for purpose” behaviour, not too dissimilar with respect to pitons, assuming of course a sound placement. Finally, the device-rock coupling dictates the pairs actual strength, thus, a correct choice and a correct placement are fundamental for all the equipment.

Table II. Estimated failure probabilities according to the type of protection and its use (last protection of the chain or belay stance).

	Last protection	Belay stance (worst case)
Pitons	28%	6%
Friends	34%	14%
Nuts	51%	17%

CONCLUSIONS

To the author’s best knowledge, the present work represents the first attempt to investigate the human capabilities to assess the reliability of a protection placement in-field. This kind of analysis is very important, since in rock climbing, higher safety levels can be achieved only by properly combining improved designs of the protection devices with increased in-field awareness of their performances.This in turn, can only derive from in-depth investigations of their physical functioning and interaction with the field environment, and of the consequent psychological implications on the climber's decision-making process. Finally, even if a limited number of available predictions has been obtained, they were sufficient to highlight some common misbeliefs in the climbing community, potentially leading to safety pitfalls and sub-optimal decision making.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests. (12).

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ORIGINAL ARTICLE

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Practical and Conceptual Analysis of Wingsuit BASE Flight

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SUMMARY

Background. Fixed object parachuting, commonly known as BASE (Building, Antenna, Span, Earth) Jumping, was revolutionized by the introduction of wingsuits in the 1990s. Wingsuit BASE Jumping (WSBJ) has since surged both in overall popularity, and more recently, in its contribution to the rising rate of BASE fatalities. Risks associated with WSBJ and its position within the broader BASE community have been explored in previous work. However, the practical considerations of a nominal wingsuit flight, the aerodynamic underpinnings of WSBJ, and discussions regarding the pilot's decision-making processes and in-flight goals are nearly absent from the current literature.
Methods. This expert opinion article was developed through years of experience in the BASE environment and analysis of in-flight altimetry and glide data from both the authors and through contributors in the wingsuit BASE community. Previous authors' rigorous investigations and thorough work on safe, high-performance WSBJ are also discussed.
Results. This concept article takes a very practical approach to WSBJ, walking through the optimal procedure for a safe jump from exit to parachute deployment.
Conclusions. Strong conceptual foundation, focus on technique, lessons from relevant accidents, and emergency planning all contribute to a successful wingsuit BASE jump.

KEY WORDS

Wingsuit, BASE, jumping, proximity, parachutist

INTRODUCTION

The advent of modern wingsuits has profoundly changed the landscape of BASE (Building, Antennae, Span, Earth) fixed object jumping. In addition to the skill sets required for skydiving and non-wingsuit BASE jumping (nWSBJ), wingsuiting BASE jumping (WSBJ) requires significant experience with wingsuit equipment, wingsuit flight, and an understanding of how the suit can influence each component of a BASE jump.

Available data clearly indicates that BASE fatalities associated with wingsuiting are representing an increasing proportion of annual BASE fatalities over the last 20 years (1-3). It is not currently known whether WSBJ is associated with a different rate of non-fatal accidents and injuries than nWSBJ. What is known is that BASE jumping injuries are most often orthopedic, with the lower limbs being the most commonly affected anatomic region (4). The rate of severe injuries in BASE, defined as those requiring recovery periods of 21 or more days, has been estimated to be 1 in 500 jumps, with less severe injuries occurring in 1 of 250 jumps (1,5).

In the time between the first BASE fatality in 1981 and the first wingsuit BASE fatality in 2001, errors associated with glide miscalculation and deployment timing only represented 11.5% of fatal BASE accidents, and no fatalities were attributed to vertical object face freefall collisions (3). From 2002-2018, since the first wingsuit BASE fatality, 30.1% of BASE fatalities are attributable to glide miscalculation or deployment timing and 5.6% to vertical object face freefall collisions (3). Wingsuits were involved in a large number of

these fatalities and may be at least partially responsible for the overall shift in fatality risk profile across the jump.
Beyond previous discussions of injury rates, fatality rates, and some work on the psychology of wingsuit BASE jumping, there is relatively little information in peer-reviewed literature on the topic of wingsuit BASE jumping (6). However, many non-academic sources, from books to blogs, are generated from within the WSBJ community on various topics within WSBJ (7-9). The purpose of this paper is to discuss ways to improve in-flight performance, explore methods of mitigating the risks associated with WSBJ, and to improve the conceptual and practical understanding of what WSBJ requires of the pilot for researchers, jumpers, and enthusiasts alike. To organize the discussion, this will be accomplished in a stepwise format that mirrors the progression of tasks in a wingsuit BASE jump.

METHODS

This phase-based understanding of wingsuit flight reflects expert opinion on the practice of WSBJ. It was developed through years of experience in the BASE environment and analysis of in-flight altimetry and glide data from both the authors and contributors in the WSBJ community. Previous authors' rigorous investigations and thorough work on safe, high-performance WSBJ were invaluable in the refinement of these ideas (7-10). This discussion is intended specifically for topics of WSBJ, and some principles may not be constructive or valid for the purposes BASE jumps conducted without wingsuits.
The methods used for the preparation of this article are not regulated by the United States, German, Israeli or Swedish legislation regarding research on humans. The authors took into account ethical issues that may have appeared through pursuing its preparation.

RESULTS: STAGE-BASED ANALYSIS OF A WINGSUIT BASE JUMP

Phase 1: the exit

The first phase of flight is composed of the initial jump from the object and the initial moments of freefall. It presents its challenges in three major ways. First, other than exceptional cases of proximity WSBJ, this is the phase of flight in which the jumper is closest to the object, increasing the risk of potentially deadly vertical or horizontal terrain strikes. Second, is the phase of flight that corresponds to the lowest total airspeed experienced in the jump. Aerodynamic control in freefall depends heavily on strong, consistent airflow, so this segment of low total airspeed flight is particularly problematic. It is for this reason that a precise exit is crucial for a successful BASE jump. Third, while most components of a BASE jump can be practiced in the relatively controlled skydiving environment, it is not currently practical for the majority of BASE jumpers to achieve a high degree of practice in zero airspeed exits in the skydiving environment. Zero airspeed skydive exits, typically performed from hot air balloons and helicopters, are very expensive and are imperfect analogues, given that the exit point is not as rigid as most BASE objects would be. In addition, they can require awkward exit stances unlike those of the BASE environment.
Importantly, very few BASE objects, such as unusually high bridges, offer a "safe" way to train the full wingsuit exit, including transition to stationary glide. These factors make wingsuit exits very difficult to train safely. It is therefore important for all wingsuit BASE jumpers to understand proper exit procedure thoroughly, as it is their main tool for quickly entering controlled flight and gaining separation from the exit object as soon as possible.
Speaking practically, three main components must be controlled for a successful exit: pushing power, pushing direction and rotation speed. The ideal footing for a wingsuit BASE exit is that of a symmetric, balanced jump from a dry, clean, sturdy object with either a vertical or inclined surface. The two-leg jump is considered to be more stable and more powerful than a single-leg jump (11). This is a kind of counter-movement jump used to achieve maximum height, but is essentially performed 'sideways' in the BASE environment. There are instances where a staggered single-leg jump can provide initial momentum that proves beneficial for certain exit points. Experienced, well-rounded jumpers will be capable of, and comfortable with, both styles. Whichever one chooses, the priorities of a strong push for exit separation, symmetry and balance must be maintained. Inclined footing, or horizontal footing with a vertical edge, is preferred because it allows the jumper to make a strong horizontal push with minimal risk of slipping, which would be more likely to occur from a horizontal force exerted on a horizontal object (**figure 1**). It is also preferred for the tips of the jumper's shoes to reach over the edge, if one exists,

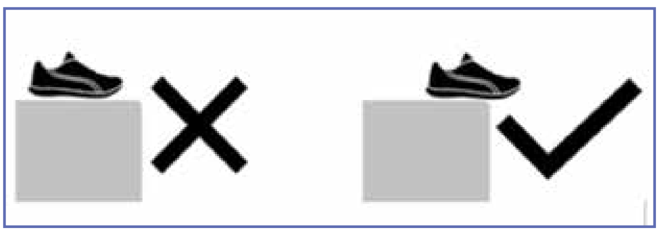


Figure 1. Preferred footing for BASE exits.

to prevent slips off the object, which are a common catastrophic error (3).

An exit's power, direction and rate of rotation have significant influence on control and stability in early flight. In the initial fall, trajectory and pitch are largely ballistic. Little aerodynamic control is available, so the focus is on making a strong push and controlling the forward rotation speed (**figure 2**). The ideal pitch for a wingsuit jump at the moment of exit is horizontal (0°), ending with controlled rotation towards a pitch of -45° at the initial moments of useful aerodynamic control.

The importance of the strength and direction of the jumper's push quickly become apparent. Some jumpers are tempted by, or may simply find it difficult to avoid, the addition of a vertical component to their exit push. However, in addition to complicating pitch control, a "head high" push with an initial positive vertical speed reduces horizontal separation from the object (**figure 4**). Jumpers should not attempt to jump upwards. New jumpers are commonly taught to keep their "eyes on the horizon" on exit. This is correct in that it indicates horizontal movement as the priority, but is misguided in that there can be a large difference between where a jumper is looking and how their body is oriented. The phrase "**push** at the horizon!" may therefore be a more accurate and useful approach in WSBJ. This way of thinking about the exit helps keep the initial pitch horizontal (0°). While the *push* is meant to be perfectly horizontal, wingsuit jumpers are more often instructed to *look* about -45°, to avoid being "head-high", a common problem associated with looking at the horizon during exit.

Quick crouch (<0.25 sec)
Stretching a muscle just before its contraction creates a more explosive jump to maximize exit push. This is considered a Counter-Movement Jump.[11]

Lean forward and tip over
This action creates rotational momentum with the feet as the rotation axis, functioning as a second-class lever. Lower crouches and tipping slowly results in less rotational momentum. By tipping forward past the object's edge, more contact with the object's vertical face is possible, resulting in a better, more stable push. This push generates all of the jumper's initial horizontal momentum.

Horizontal push: legs straightened (1) and hips forward (2)
The forward rotation rate can be controlled by straightening the legs and pushing the hips forward, in a motion similar to a back flip. Manipulating the moment of inertia in this way is like a dancer who straightens a leg during a spin to slow their rotation rate.

Tense the arm wing (3) *before* the leg wing (4)
The center of lift from the arm wing, which is greater than the lift of the leg wing, is forward of the center of mass and therefore opposes forward rotation. For this reason, arm wing tension, straight legs with hips forward, and a collapsed leg wing are all crucial in controlling rotation rate and avoiding a head-low exit.

Figure 2. Wingsuit BASE exit procedure (Picture: Lino Oehl).

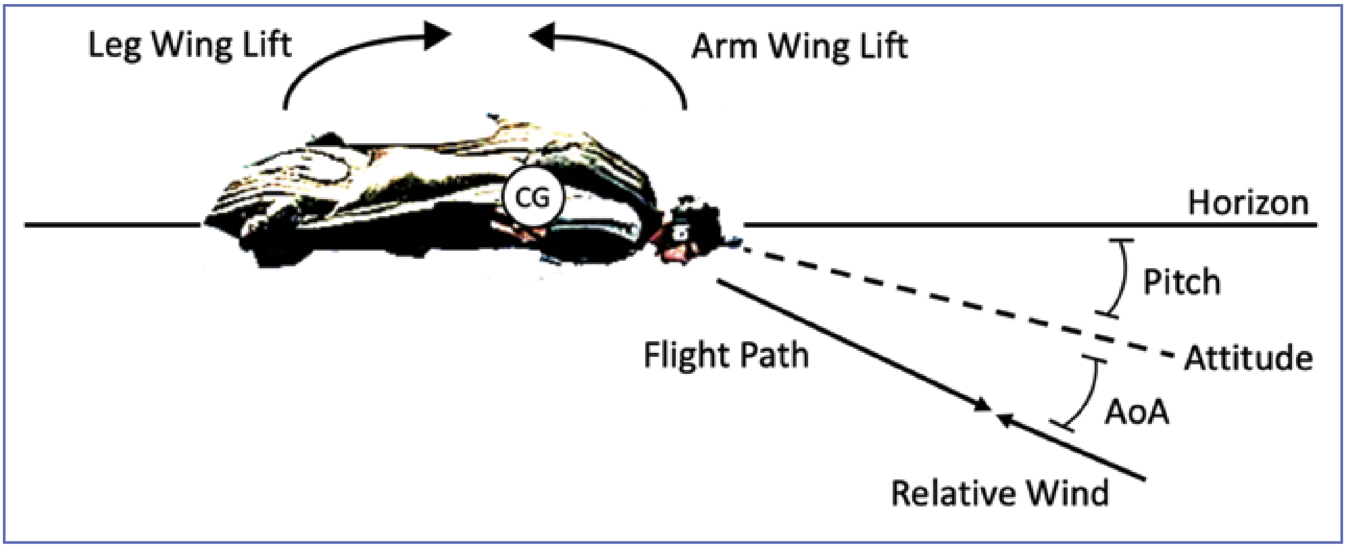


Figure 3. Wingsuit free-body diagram (CG = Center of Gravity, AoA = Angle of Attack, adapted from TopGun BASE10 and Robson and D'Andrea 201012, photo from the personal collection of Author J.S.)

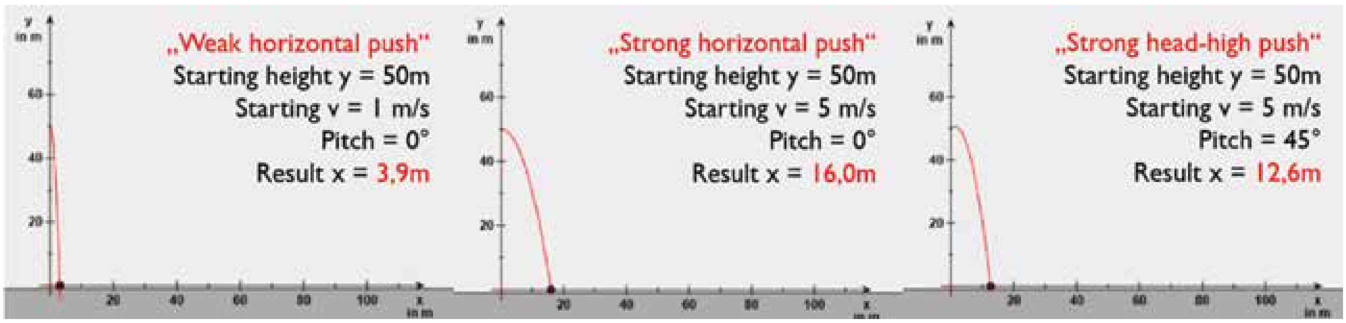


Figure 4. Projected ballistic trajectories and corresponding exit parameters.

Using widely available GPS- and altimetry-based flight equipment, jumpers can analyze their own exit performance. The ideal exit is one with maximized horizontal speed and vertical speed near zero at the moment of exit. Speaking practically, in analysis of one's glide data, a good push will create a horizontal speed greater than the initial vertical speed. The better the push, the farther apart those two speeds will be.

Some exit points are "underhung", meaning that some lower altitude portion of the object extends horizontally beyond the exit point itself in the same direction of the jumper's initial push. On an object like this, falling straight down from the exit point would either be impossible or would guarantee object impact. A strong exit is imperative to avoid object collision, as there are many fatal incidents due at least in part to a weak exit.

The theoretical scenario for these accidents is as follows. A wingsuit BASE jumper at an underhung object performs an uncharacteristically weak exit. This leads to insufficient horizontal object separation and a collision with the object almost immediately after jumping. The force of impact makes establishing aerodynamic stability impossible and the jumper fatally impacts the ground or the cliff a second time soon after. Unfortunately, this scenario has been rather common in WSBJ.

Phase 2: The Start

'The Start' is the period of the initial dive from the establishment of -45° pitch until the flattening of pitch and the establishment of glide. As the exit phase closes, minimum total airspeed has developed in the initial freefall to estab-

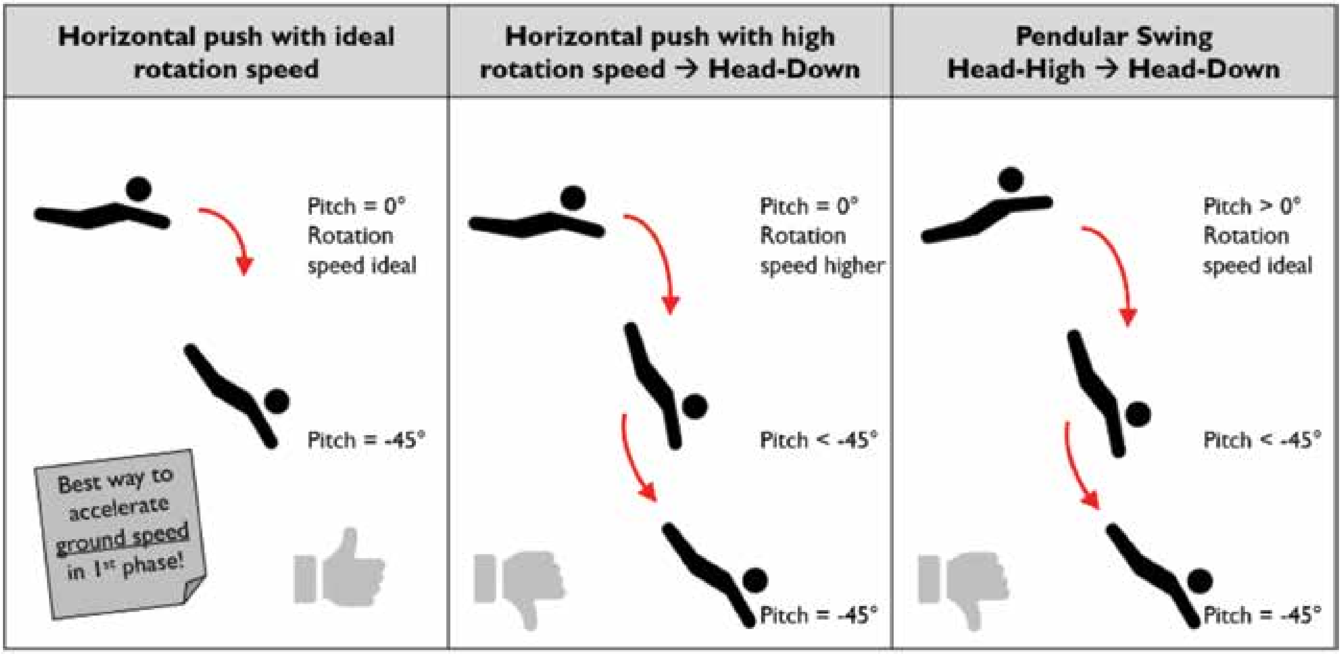


Figure 5. Pitch variation and object separation concept.

lish aerodynamic control. At this point, the decision can be made to recover quickly and establish the stationary glide ratio as soon as possible, known as the short exit, or to continue diving in order to continue building speed, known as the race exit (**figures 6**, **7**). Whichever the pilot chooses, the suit's initial aerodynamic stall transitions to glide and tension is applied to the leg wing. The pilot's pitch, understood as angle between the wingsuit's chord line and the horizon (**figure 3**), is maintained constant at -45° throughout the second phase. In contrast, as the horizontal airspeed continues to increase, the angle of attack (AoA) slowly decreases as the relative wind shifts from being vertical (from directly below) to horizontal. For a short exit, this phase is typically around 0.5-1.5 seconds, but is maintained

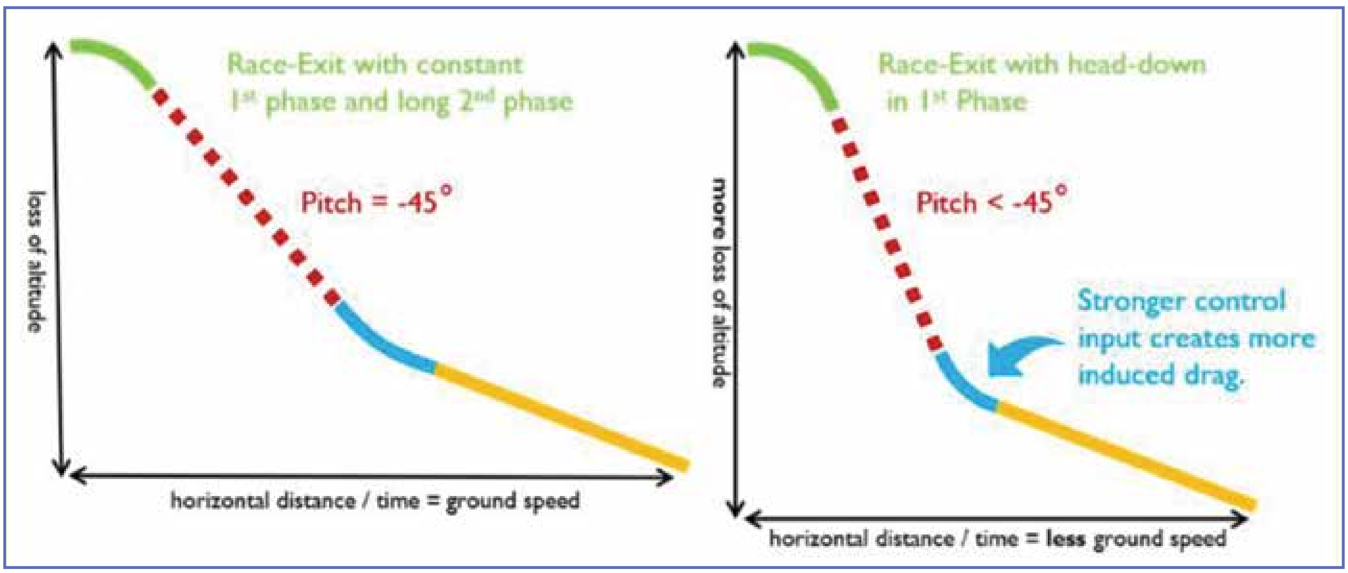


Figure 6. Race exits and exit orientation conceptual diagram.

for up to 10 seconds in some race exits (**figure 8**). However, these are only general descriptors. Specific time intervals must be re-evaluated based on the goals and needs of each jump and jumper.
While all exits are meant to be safe, some jumpers elect to follow different strategies for different jumps. Jumpers usually employ the short exit to achieve maximum horizontal glide with the smallest possible loss of altitude. This ultimately conserves energy and maximizes glide capacity later in the jump. In contrast, the race exit is a procedure intended to maximize groundspeed at the expense of glide. Some jumpers believe that by exiting "head low", with a higher forward rotation speed and end-exit pitch below -45°, they can improve their race exits. Robust data do not yet exist on this subject, but the theory behind this approach may be misguided for three reasons. The first two have to do with safety, and the third being that this procedure may in fact obstruct the race exit's primary goal, maximizing groundspeed.
First, a dive pitch below -45° compromises one's ability to adequately separate from the object, creating a safety hazard. Secondly, by training this exit, one risks interfering with muscle memory for a normal maximum-separation exit. Cases do exist where the habit of performing race exits on every jump has led to jumpers unintentionally using this procedure at objects requiring short exits (unpublished communication, Amrei Stöckl and Lino Oehl). Third, while the decreased initial AoA provided by a head-low exit (pitch < -45°) does cause a quicker increase in airspeed through reduced drag, one must consider that this reduced AoA also requires higher airspeed to produce useful lift when compared to a normal-pitch exit, which compromises horizontal acceleration. Just because an exit achieves high airspeed more quickly does not necessarily mean a net increase of ground speed exists across the jump, which is the goal of the race exit. In this way, an initial pitch <-45° may be self-defeating in horizontal speed outcomes in addition to compromised safety, as previously mentioned.
In terrain proximity flight, exits with pitch <-45° are sometimes performed with the intention of achieving aerodynamic control as quickly as possible. This shares similar problems as when a race exit is performed head-low (pitch <-45°). The safety problems are similar, but also include compromised long-term glide in the case of proximity flights with a "flatter" overall glide profile. Regarding performance, it must again be considered that a steeper pitch (pitch <-45°) results in a smaller AoA in early flight, which requires a higher total airspeed to be useful than the same wing at a higher AoA, up to the AoA_{STALL}. This steep exit pitch may result in delayed aerodynamic authority. However, steep pitch (<-45°) may be entirely proper in proximity flight after aerodynamic control is attained, given the unique goals and safety procedures of terrain proximity flight.

Phase 3: Glide Transition

'Glide Transition' represents the transition from a dive to the stationary glide phase of flight. By the end of this phase, the total airspeed is constant, and acceleration has stopped. By recovering from a dive, the pitch becomes more horizontal. However, because the horizontal speed is increasing, the AoA does not meaningfully change until the target glide speed is reached. Imprecise or aggressive control inputs and

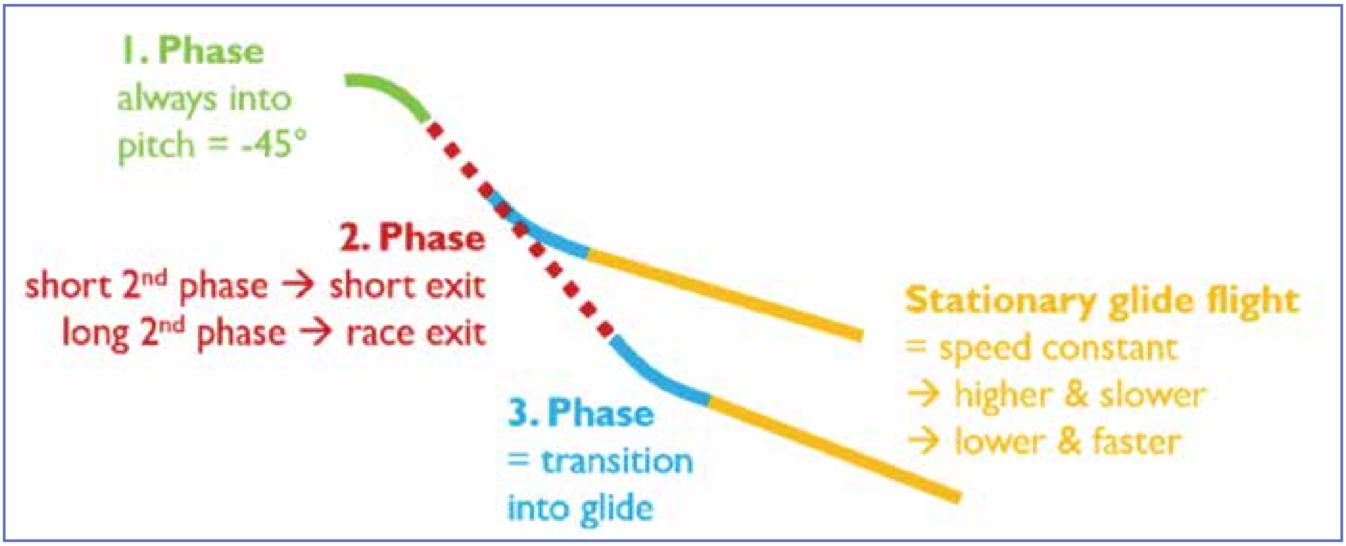


Figure 7. Flight Phase illustration.

body position result in energy loss to drag and reduced glide capacity-common issues in this phase.
These initial three phases of wingsuit flight require skill sets that are quite different from those of non-wingsuit BASE jumps. In early BASE training, jumpers learn to jump "head-high", with a pitch at or above the horizon (pitch > 0°). This muscle memory must be overwritten to properly execute the horizontal push, pitch control and AoA control necessary for WSBJ.
A way to visualize these initial phases is to imagine a -45° reference line coming down and out from the exit point. The point at which a jumper's glide path passes this imaginary reference line can be understood to represent their "start-arc" (8). While this metric does not account for total airspeed attained at that moment, it can be one way to understand exit performance, when properly contextualized. A sample of altitude and GPS tracking data in short and race exits is available in **figure 8**. When improving exits, jumpers are often tempted to buy bigger and more advanced wingsuits in order to artificially inflate their abilities. However, better theoretical understanding, education, and experience are much stronger steps towards the safe, proper development of a BASE jumper than using equipment to fill skill gaps.
It is important to define what is meant by a "short exit", given that it may refer to the quickest crossing of the -45° line or the least amount of altitude lost at some other time point. Stated simply, the duration of phase 2 and the desired speed to reach during phase 3 must be chosen carefully based on exactly where in the flight profile the altitude loss

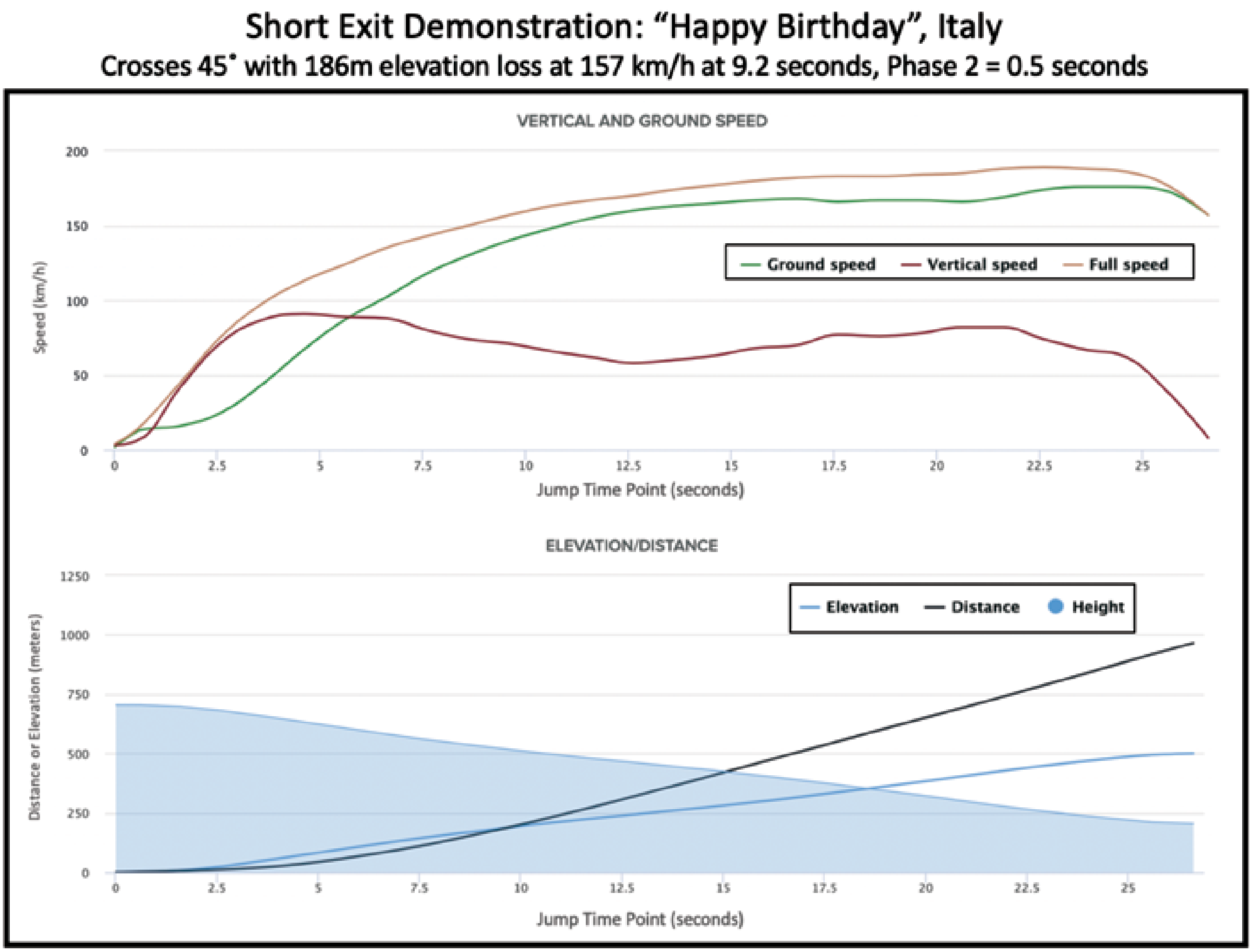
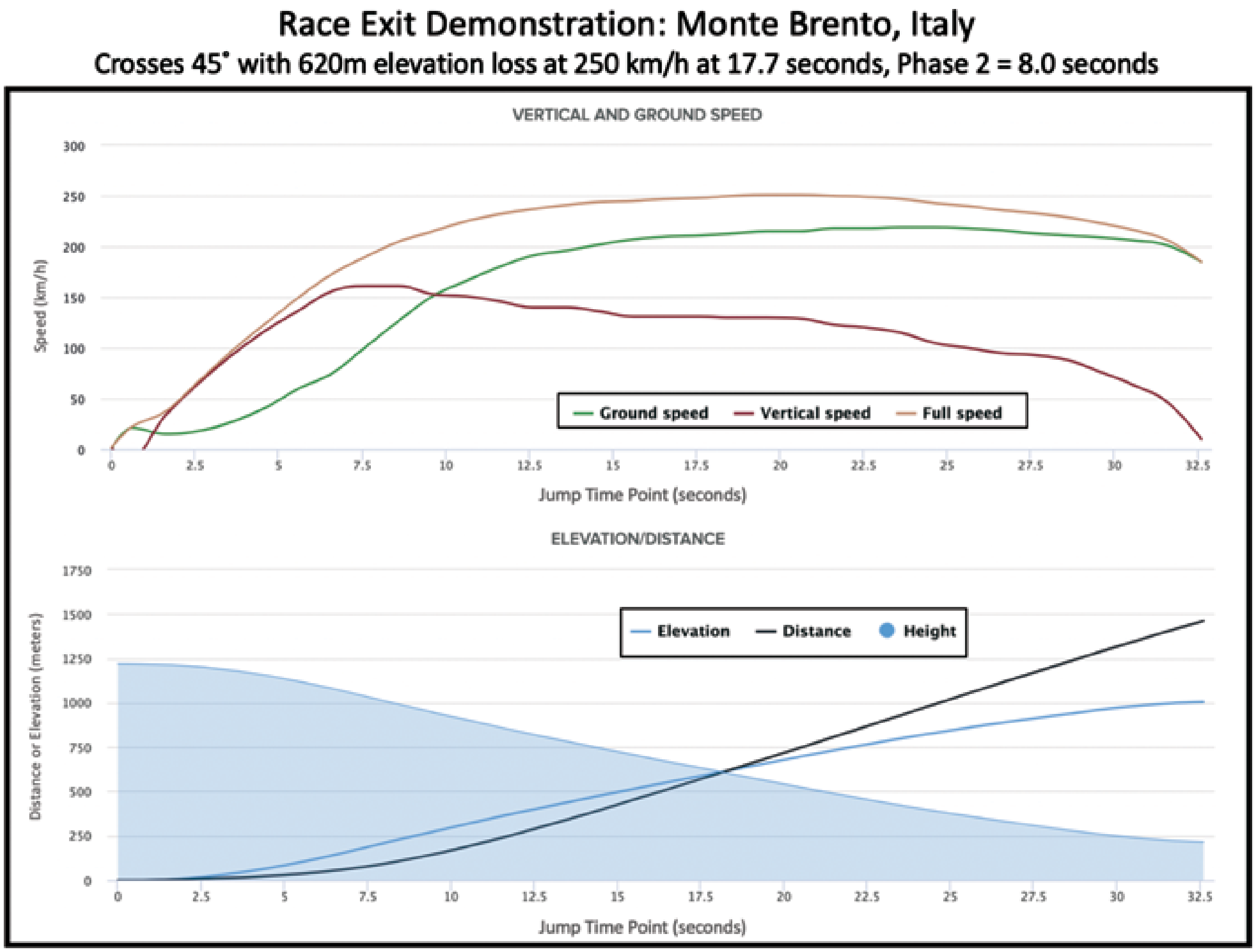


Figure 8. Sample glide data for each exit type (Same pilot [Lino Oehl], same wingsuit [Colugo 3], same first phase exit procedure, and comparable weather conditions).



must be minimized. The best start arc is typically achieved when phase 2 ends at the suit's minimum airspeed for flight. This minimizes altitude loss at the crossing of 45° from the exit point, but does not provide the best glide for the jump as a whole. This is because the speed at the end of phase 2, in that case, would be less than the suit's best glide speed. To maximize glide at any distance beyond the start arc, phase 2 needs to end at the suit's airspeed of best glide. The tradeoff between these two types of altitude-saving measures must be navigated with care based on the glide goal for and risks presented by each jump. The start arc is not the whole picture when it comes to glide and total airspeed needs to be accounted for in the discussion of short starts.

A good exit is the appropriate use of potential energy for that object and context based on glide, speed, and safety goals, with aerodynamic control starting as soon as possible. For these reasons, a start arc does not completely capture the notion of a short exit or the overall quality of any given start. The definition of good performance on a wingsuit flight always depends on the jumper's goals and the demands of the object.

Phase 4: Stationary Glide Maintenance

The stationary glide phase of a WS BASE jump extends from the establishment of glide speed to the beginning of deployment or the pre-deployment flare. This phase typically occupies the largest portion of time spent during a WSBJ. The stationary glide phase requires a continual, careful analysis of one's resources (altitude, speed, alternative routes), the challenges presented by the ongoing jump, and the adequacy of those resources to meet the evolving challenges. Familiarity with the terrain and slope, the altitude necessary to safely cross each region of potential flight, knowl-

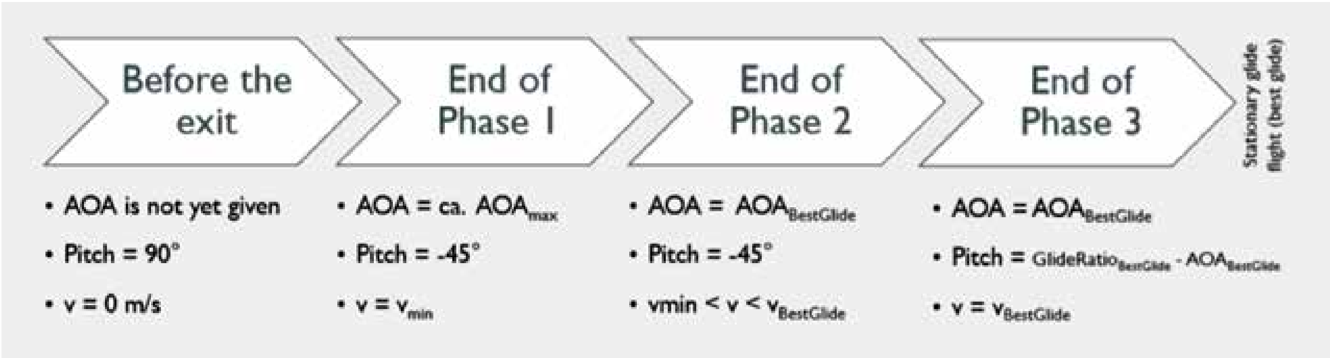


Figure 9. Aerodynamic stage definitions for shortest possible exit at best glide speed (AOA = Angle of Attack, v = Velocity, ca = approximately).

edge of available landing areas, and local weather expertise are among the knowledge that must be established before a jump can even be considered. Then, during the flight, a wingsuit pilot must be experienced with estimating their glide, relative altitude, and airspeed adequacy by feel, with or without a functioning glide monitor. These two data sets, resources and risks, must then be compared moment-by-moment, with decisions being made by instinct and experience, given the lack of time for contemplative thought. In these ways, pre-flight planning and preparedness are crucial for success in stationary glide (**figure 9**).

Emergency routes are key components of a thorough pre-flight plan. Commonly known as "outs," these alternative routes typically improve safety by allowing for more immediate altitude loss than the initially-selected route. Any number of other factors can lead to a situation where the primary route is no longer possible, such as inadequate altitude, insufficient airspeed, equipment problems, or medical issues, among others. A good "out" typically allows the jumper to safely regain airspeed and terrain separation, or at the very least provides a different route to a safer landing area. Casually acknowledging that a different route exists is not adequate. Understanding the outs' characteristics, terrain descent profile, where they lead, if they have any landing areas, their weather considerations, and how one can communicate with their group after landing are among the factors that must be well understood before relying on any route, primary or otherwise.

In more advanced jumps, there are likely to be sections of the planned jump where no outs exist. Theoretically, the safest option is to avoid jumps where this is the case. However, if one chooses to undertake these jumps, steps can still be taken to improve safety. Any section with no outs should be entered with as much speed and spare altitude as possible, to build margin for unexpected energy losses or imperfect glide maintenance. In addition, a landmark before the final out should be identified at which the jumper positively confirms to themselves that they securely have the altitude and airspeed to successfully navigate the following section. The purpose of this landmark is similar to that of the "decision altitude" in skydiving. It is a point past which the emergency route is automatically taken unless the primary option can confidently be employed. Lastly, at all times, but particularly in sections with no out, jumpers should be mentally prepared for a "panic pull," an immediate emergency parachute deployment in a suboptimal time or location, at any point. If a jumper's glide is worsening, terrain clearance is decreasing, or the jumper is noticing themselves slowing down or pitching up more than normal to maintain altitude, parachute deployment before the situation deteriorates any further is reasonable. Obviously, this is not ideal, but many fatalities and injuries have occurred as a result of waiting too long for an emergency deployment.

In proximity flight, jumpers choose geographic routes shaped to allow flight very close to the object for some period of time. A route's specific combination of geography and flown altitude can be referred to as a "line". High airspeed and proper line selection are crucial to success in proximity flight. A jumper with a consistently high airspeed can pitch up or flare at any moment to quickly gain separation from the object. Jumpers new to proximity flight are often taught to select lines that require them to intentionally dive, such that only intentional movements could force them further down. Anything other than purposefully diving harder would cause them to flatten their glide and separate from the terrain because of the high airspeed. Training of this sort on steep terrain reduces the likelihood of collisions and trains the habit of diving to terrain, rather than pitching up and hoping that one's airspeed will be adequate to clear the object.

As a matter of principle, subtle movements, stability, and well-refined body position will allow the maximum conversion of altitude into speed, rather than losses to drag or exaggerated adjustments in body position.

In training for proximity flight, jumpers will often fly the same route multiple times, reducing object separation slightly with each successive attempt. This represents a series of nearly identical lines, differing only in altitude. In this type of training, altitude should be lost in a way that contributes to airspeed (through diving), rather than by flying in an intentionally inefficient way or through maneuvers such as "s-turns". In addition, the jumper should only continue on a new line with less object separation when they are at peak performance on that jump. Going lower, or even at the same level of proximity, with an imperfect exit, recovery, or glide may diminish more safety margin than the jumper's experience can tolerate. Even without noticing it, the jumper may be flying a higher AoA to hold the same line, which may not be recoverable. A comparably safe way to train this is by use of a variable inclination wind tunnel (13, **figure 10**).

There are many WSBJ fatalities attributable to glide miscalculation. Interestingly, there are at least three cases in which wingsuit BASE jumpers have survived terrain collision that occurred due to glide miscalculation. In each of these, the jumper did not have the altitude or airspeed required to fly the selected line. The classic progression of this accident is that a jumper will commit to a line with no outs, notice that they are lower than they planned and therefore, consciously or otherwise, pitch up to regain the lost altitude. This pitch adjustment helps maintain altitude momentarily, but costs airspeed. Eventually their airspeed runs out, the angle of attack increases past the stall point, and aerodynamic lift is lost, resulting in terrain collision. Situational awareness, selecting lines appropriate for one's performance and experience level, and actively considering "outs" are the simplest solutions to this problem.

Figure 10. Wingsuit pilots training in an inclined wind tunnel (Stockholm, Sweden) having a variable inclination range that covers the stationary glide performance of current wingsuit models. Take-off and landing are from/to the floor, meaning that only Phase 4 can be realistically trained. Photo courtesy of Espen Fadnes and Håkan Nyberg.

Phase 5: Flare

Before deployment, it is possible to convert kinetic energy from horizontal and vertical speed back into altitude with a maneuver called a flare. This procedure allows for deployment at a slightly higher altitude and lower airspeed, which improves jumper safety. During a flare, the angle of attack is increased, slowing vertical fall rate, increasing horizontal speed temporarily, causing a short gain in altitude, and ending with a decrease in total airspeed. Put simply, kinetic energy from the vertical fall rate is converted into horizontal speed through increased AoA. Kinetic energy from this high horizontal speed is then converted into potential energy from increased altitude as the horizontal speed deteriorates in the climb.

This maneuver is not simple and must be practiced in the skydiving environment before it can be executed well in WSBJ. It requires precise execution because it can involve controlled flight at both very high and very low airspeeds, both of which can make a wingsuit difficult to control immediately before deployment. In addition, because this maneuver is used at the end of a jump, an asymmetric or unstable flare typically cannot be repeated due to altitude restriction. A common misconception is that long, high speed dives are necessary for a strong flare. However, effective flares can be conducted without such dramatic expenditure of altitude, and some degree of flare is possible even from the relatively low speed of best glide.[8] If flaring from a very high airspeed, the rate of AoA change must be carefully controlled to avoid a high-speed stall and may not be more effective in regaining altitude than if the maneuver were initiated from Phase 4 airspeed.

Phase 6: Canopy Deployment

Canopy deployment presents many risks to BASE jumpers. From equipment failures to malfunctions and opening in a direction different than the direction of flight (off-heading), there are many ways that deployment can quickly create dire problems for BASE jumpers. In addition, the problem of limb confinement within the wingsuit can amplify these issues for wingsuiters, who may not be able to operate their primary canopy flight controls for a number of seconds after deployment.

For these reasons, a history of consistent, on-heading deployments in nWSBJ and wingsuit skydiving are absolutely necessary before transitioning to WSBJ.

Many WSBJ fatalities are associated with technical errors at deployment. Two common avoidable issues are “missed pulls,” when the jumper is not able to find the pilot chute to begin deployment, and catastrophic flight instability occurring because of asymmetric, stalled, or prolonged deployment procedures. Familiarity with one’s BASE equipment, currency of flight experience, responsible packing, vigilant gear inspection and maintenance, and well-practiced deployment technique can all help avoid these issues at deployment. Lastly, as previously mentioned, emergency deployments (“panic pulls”) can lead to dangerous landing situations, but if it becomes clear that a jumper lacks the airspeed, altitude, or stability to successfully complete the flight with adequate safety margin, it may be in their best interest to deploy sooner rather than later. Jumpers must always be mentally prepared to do it.

SUMMARY

An exit with a strong horizontal push and controlled rotation to a dive with pitch of -45°, reached at minimum airspeed of aerodynamic control, is ideal (Phase 1). Ballistic rotation can be controlled up to this point by straightening one’s legs, pushing the hips forward, and tensing the arm wing. This dive (Phase 2) is maintained at a pitch of -45° for a duration of time suited to the goal and requirements of the individual jump. Jumpers then use gentle control inputs to establish their speed and AoA based on the goals of the jump (Phase 3). The AoA is held constant during Phase 3, which finishes when the speed of best glide is reached. This glide speed and AoA are then maintained for the duration of the jump, or adjusted as appropriate per the jump’s goals, with constant vigilance regarding one’s altitude, speed, and available outs (Phase 4). A flare can then be conducted to slow one’s airspeed and regain altitude temporarily (Phase 5). The jump then concludes with a smooth, controlled, symmetric deployment (Phase 6).

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (14).

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MINI-REVIEW

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Altitude Training and Endurance and Ultra-Endurance Performance

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SUMMARY

Background. Altitude training has been shown to improve endurance and ultra-endurance performance at altitude, whereas the possible benefits from altitude/hypoxic training for competing at sea level have been, and still are, a matter for debate. Reasons for this discrepancy may result from the variety of protocols utilized in terms of altitude, natural or simulated, to which the athletes were exposed, and amount of the time spent at altitude. In order to conciliate previous findings and provide practical recommendations to athletes, the concept of optimal "hypoxic dose" has been defined.
Methods. To perform a review of the literature concerning the effects of altitude training on athletic performance.
Results. The dominant paradigm is that the improved performance at sea level is due primarily to an accelerated erythropoiesis due to the reduced oxygen available at altitude, leading to an increase in red cell mass. Indeed, in recent years it has become evident that other non-hematological factors (improved muscle efficiency, greater muscle buffering capacity, etc.), may contribute to improve athletic performance.
Conclusions. Despite more than fifty years of research and studies, altitude training remains a controversial issue and yet, there are many unanswered questions.

KEY WORDS

Endurance performance; haemoglobin; Live High-Train Low; neocytolysis

INTRODUCTION

Altitude/hypoxic training has been used since the 1960s by endurance athletes in an attempt to improve sea level performance. The original method of altitude/hypoxic training was one in which athletes lived and trained at moderate altitude (1500–3000m), for the purpose of increasing erythrocyte volume and ultimately enhancing sea-level maximal oxygen uptake (VO_{2max}) and endurance performance. Live high - train high (LHTH) altitude training is still used today by sea level athletes who complete altitude training camps at specific times during the training year (1), and of course by altitude residents, such as the Kenyan and Ethiopian runners. However, one major conclusion drawn from both anecdotal and scientific evidence regarding LHTH altitude training, was that endurance athletes did not seem able to train at an equivalent or near-equivalent training intensity (e.g., running velocity) as compared with sea-level training. Thus, there may be a detraining effect associated with LHTH, which likely accounts for the evidence that, when appropriate control groups have been included, living and training at altitude have not been proven to be advantageous compared with equivalent training at sea level (2).

To overcome this limitation, Levine and Stray-Gundersen (3) proposed the "live high train-low" (LHTL) model about twenty years ago. The general idea was that if athletes could live and sleep at altitude but train at sea level, they could acquire the physiological advantages of altitude acclimatization for maximizing oxygen carrying capacity, without the detraining associated with hypoxic exercise. In their original study (3), 39 college runners underwent 2 weeks of lead-in training and 4 weeks of controlled sea-level training where after the subjects were randomly assigned to 4 weeks of either living at 2500 m and training at 2500–2700 m (LHTH), living and training at sea level (Control), or living at 2500 m while training at lower altitudes between 1200 and 1400 m (LHTL). Following the various training camps, VO_{2max} was increased with LHTH and LHTL, but 5000 m running performance was only significantly increased in the LHTL group (3).

Over the last two decades, a large amount of research has been conducted adopting the LHTL approach in endurance athletes of different disciplines and competitive level, leading to controversial results. Several studies (4,5,6,7) and meta-analyses (8) support the sea level performance benefit of properly executed LHTL altitude training, whereas others have failed to do so (9) and question the usefulness of this practice (10,11).

At a glance, most of these studies have used small sample sizes and present limitations in the study design, such as the lack of a control group, that do not allow to rule out the occurrence of placebo, nocebo and training camp effects (8,10). Numerous reasons may explain this discrepancy. Because the geography of many countries does not readily permit LHTL and due to practical (logistically and financially) constraints, it may not be convenient for athletes to spend time at natural altitude. To overcome this potential problem, studies have been conducted substituting "terrestrial" altitude exposure (hypobaric hypoxia) with the use of 'nitrogen housing', where indoor living areas are flushed with N_2, or use of molecular oxygen sieves to decrease FIO_2 and thus stimulate exposure to high altitude (normobaric hypoxia). Whereas, it seems that for the same inspired partial pressure of oxygen, the erythropoietic responses leading to the increase in haemoglobin mass is similar (12), others various biological markers such as ventilation and nitric oxide metabolism show a different behavior (13). While still largely debated (14,15), it currently remains unresolved if normobaric and hypobaric hypoxic exposure elicit different physiological or pathophysiological responses.

Another factor to be considered is the iron status of the athletes involved in these studies. As reported by Stray-Gundersen et al., (1992) (16), no increase in red cell mass (RCM) or VO_{2max} occurred in nine iron-deficient distance runners (serum ferritin <30 ng/mL for men, <20 ng/mL for women, before departure) after 4 weeks at 2500 m, while athletes with adequate ferritin levels pre altitude demonstrated significant increases in RCM and VO_{2max} post altitude camp. Indeed, emerging data suggest that iron supplementation may be a necessary requirement for adequate erythropoiesis with altitude exposure (17). In turn, this may explain why some of those studies failed to demonstrate improvements in VO_{2max} or performance following altitude training.

Regardless of iron status pre altitude, individual variability in the response to altitude/hypoxic exposure is an important factor that needs to be accounted for when planning altitude training and specific living/training elevations (18). Different responses between athletes have been reported for various parameters such as the EPO response to both short- and long-term exposure to hypoxia, ventilator acclimatization, and ability to maintain training volumes and intensities at altitude (18). Overall, the balance between those adaptations, or lack thereof, will determine whether the athlete will experience improvements in VO_{2max} and performance following chronic hypoxic exposure. In this regard, ongoing research is devoted to identify the specific characteristics (genotype or phenotype) that influence the observed individual variation in the altitude/hypoxic acclimatization response.

Interestingly, in attempt to conciliate the inconsistent findings of the literature and to provide practical recommendations to athletes and coaches, the concept of optimal "hypoxic dose" has been defined (19,20). Given the variety of protocols used in LHTL studies in terms of: 1) the altitude—natural or simulated—at which the athlete was exposed; 2) number of days of altitude/hypoxic exposure, and 3) number of hours per day of altitude/ hypoxic exposure, researchers have focused on the question: in using LHTL, what is the optimal hypoxic dose needed to produce the expected beneficial physiological responses and sea-level performance effects in most participants? Obviously, there is no "one size fits all" model when considering altitude training, however Constantini et al., (2017) (17) have recently summarized current best-practice altitude training guidelines to optimize sea level endurance performance. The information provided is based on evidence-based practices from multiple laboratories and anecdotal observations by the authors and others. While the specific response to altitude is highly individualized, following these guidelines and recommendations will help improve the odds of a successful altitude training camp outcome.

Physiological mechanism(s) responsible for the improved performance after altitude training

Exposure to environments with reduced partial pressure of oxygen (PO_2) induces a number of physiological adaptations that are potentially beneficial for athletic performance. The prevailing paradigm of adaptation to a lower O_2 availability, either in natural or simulated hypoxic environment, is an increased synthesis and release of EPO that, given adequate iron stores, leads to an increased rate of red blood cell production and hemoglobin mass (Hb_{mass}). These hematological changes improve oxygen carrying capacity and are partially responsible for the improvement of sea level VO_{2max}. Although some authors have explicitly related the change in sea level performance following an altitude training camp to the change in serum EPO levels[3, 21] at altitude, the correlation for the change in VO_{2max} versus the change in red blood cell volume yielded an r^2=0.137[3]. This means that 86% of the variance in VO_{2max} is attributable to factors other than the change in Hb_{mass}. Incidentally, it is important to be aware that VO_{2max} is not the sole determinant of performance. Among elite athletes, other factors such as exercise economy and the fractional utilisation of VO_{2max} are also important determinants of endurance performance[22]. In addition to the increase in Hb_{mass}, a number of nonhematological factors, such as an enhancement of muscle efficiency and of both muscle buffering and ability to tolerate lactic acid production, have also been proposed to contribute to improved sea level performance following altitude training (see the review of Gore et al., 2007) (23). Consistent with this view, is the observation that high altitude natives have shown a better economy of locomotion than sea level residents (24).

Time to return to sea level

Another key unanswered question, which is rarely addressed, concerns the proper timing of return to sea level prior to competition (25). So far, researchers have been almost exclusively focused on the mechanisms and time course of altitude acclimatization and there is a paucity of data on the time course of de-acclimatization from altitude. Indeed, mistiming of the return to sea level can potentially result in the athlete performing worse than pre altitude. At present, there is meager evidence based research on optimal timing of return for enhanced sea level performance, and most recommendations are based on anecdotal evidence from coaches. Three physiological mechanisms should be considered when timing the return to sea level prior to competition: (1) red blood cell mass decay, (2) ventilatory acclimatization, and (3) biomechanical/neuromuscular adaptations associated with force production.

With regard to the first and likely most important mechanism, it has recently been observed how the red cell mass (26) or the total Hb_{mass} (27) of subjects acclimatized to altitude rapidly decreased by 10% to 15% over the first few days after descent to sea level. This physiological process, defined neocytolysis, is characterized by a selective hemolysis of the youngest circulating red blood cells when EPO levels fall below resting baseline levels. Whether periods of intermittent hypoxia, either at night while sleeping or even with the hypobaria of airline travel, could result in enough EPO release to prevent neocytolysis and preserve the hematological acclimatization response for a longer time is matter of future research (25). At present, the proper timing of return to sea level prior to competition remains elusive from a physiological point of view. Given the large individual variability, it is likely that each athlete may display his or her own signature of de-acclimatization with sea level residence, and knowledge of personal decay rates may allow for individualized prescriptions of when best to complete post altitude camp (25).

Preparation for ultra-endurance performance at altitude

Whereas the possible benefits from altitude/hypoxic training for competing *at sea level* have been, and still are, a matter for debate, the usefulness of this approach to improve endurance and ultra-endurance performance *at altitude* cannot be questioned. Given the wide proliferation of ultra-long endurance races held at moderate (for instance the Tor des Géants, a foot race on a distance of 356 km reaching 3000 m with a positive altitude difference of 27 km) and high altitude (for example the Himal Race 2020, 850 km distance up to 5364 m with a positive altitude difference of 40 km), it is of paramount importance for athletes engaged in these events to know whether a sojourn at altitude prior to the competition will be useful or not.

It is well established that endurance performance of sea level dwellers is impaired acutely upon arrival at moderate altitude, mainly due to a large drop in arterial oxygen saturation and gradually improves due to ventilatory acclimatization and an increase of the haematocrit. As a result, since the Summer Olympic Games 1968 held in Mexico City, athletes, coaches and mountaineers are required to establish optimal preparation programs for competing at altitude.

From the analysis of the literature, an exposure to hypobaric hypoxia of at least 2 weeks seems to be necessary to achieve a proper acclimatization and compete at the optimal level in ultra-endurance events held at altitudes up to 4,500 m. However, in some situations, such an ideal acclimatization profile cannot be realized for logistical, socioeconomic and/or individual reasons. When time for a proper acclimatization is not available, a “pre-acclimatization”, the exposure of the body to real or simulated altitude for even an intermittent, limited duration, may represent an option. Unfortunately, there is not yet much scientific evidence about the optimal approach (altitude, duration of hypoxia and duration of normoxia between the hypoxic phases) to adopt. In order to reduce the risk of high-altitude illness, the recommended strategy is to remain at an altitude between 2000 and 3000 m for about a week and to include day hiking or climbing at higher altitudes (28). Profound knowledge and consideration of the individual differences in the physiological responses to a sojourn and training at altitude is essential to coaches, team doctors and athletes for competitive success (29).

CONCLUSIONS

Although the current scientific evidence is somehow controversial, there is a widespread acceptance that altitude training can enhance endurance performance at sea level. As a matter of fact, since the relative improvement in performance required by an elite athlete to increase their chance of winning medals at international competition is about 0.5% (30), it is not surprising that with small sample sizes (less than 20 participants), many studies have been underpowered to detect a change of this magnitude using conventional statistics.

Current guidelines for optimal altitude training in order to enhance sea level endurance performance have been recently summarized (17). While the specific response to altitude acclimatization and de-acclimatization is highly individualized, following the proposed guidelines and recommendations will help improve the odds of a successful altitude training camp outcome.

More research, with a robust study design, should be done to determine whether or not altitude training leads to improvements in sea level performance.

CONFLICT OF INTERESTS

The author declares that he has no conflict of interests (31).

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ORIGINAL ARTICLE

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Accidents and Risk Related Behaviours in Downhill Mountain Biking in Regard to Trail Choice

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LEVEL OF EVIDENCE: 3b

SUMMARY

Background. Downhill mountain biking (DMB) is a subdiscipline of mountain biking. Rider skill seems to be the most influencing variable for DMB performance. In order to classify skill level, the aim of the present study was to investigate DMB-participants in terms of accident involvement, demographic and psychological variables, and to categorize them after their completion of trails (easy vs difficult) in a bike park.

Methods. 190 DMB riders (DMBR) were asked about their accidents, injuries and psychological variables at two different bike parks (**table I**). 112 answered the questionnaire after completing an easy trail (ET; 4^3+B or 4^2+B) and 78 after a difficult trail (DT; 8^3+B or 8+B). To calculate group differences, Mann-Whitney U and Chi² Tests were used.

Results. Significant differences detected that DT riders were younger, consisted of more males, had more experience in years and higher frequency per week than ET riders. No significant difference was found in accident involvement. All but one person reported to wear at least a helmet as protection equipment. Knee and back protection usage was significantly higher in DT riders. DT riders perceived their sport as more dangerous, reported higher deliberate risk-taking and experienced higher sensations during DMB.

Conclusions. The differences between ET riders and DT riders show the need of preventive steps, such as risk assessment capability, even for more experienced riders.

KEY WORDS

High-risk sports; extreme sports; motives; protection equipment.

BACKGROUND

Mountain biking was started in the USA in 1976 (1). As with many adventure sports, mountain biking originated as a niche activity. Today, however, it involves many, clearly distinguished subdisciplines such as Cross-Country, Dirt Jumping, Freeride, All-Mountain/Enduro and Downhill Mountain Biking (DMB) (1). DMB is a racing-oriented subdiscipline of Mountain Biking consisting of high velocity runs (up to 70 km/h), jumps and narrow turns on hard, rocky and uneven terrain which involves the risk of serious, even fatal injuries (2, 3, 1). Cohen et al (2018) (4) suggested using the term extreme/high-risk sports when referencing a sport which is "a predominantly competitive (comparison or self-evaluative) activity within which the participant is subjected to natural or unusual physical and mental challenges such as speed, height, depth, or natural forces. Moreover, an unsuccessful outcome is more likely to result in the injury or fatality of the participant more often than in a 'non-extreme sport'" (p. 6).

Accidents and injuries occur frequently in DMB. In a prospective study of one summer season (April-September), 494 injuries occurred in 249 questioned riders. Most of these injuries were mild (65%) with contusions and abrasions as the major injury types (56% and 64%). Of the injuries, 13% were severe; 41% of which led to restraint from DMB of more than 28 days (2). In a retrospective data collection of competitive and recreational DMB athletes, competitive athletes had a significantly higher injury rate than recreational ones (79% vs 50%), but also had a higher exposure time (16.3 ± 9.5 h/week vs 7.4 ± 5.8 h/week) (5). When normalizing for time of participation, the incidence of injuries was only slightly higher in World Cup athletes than in recreational athletes (0.69 vs 0.60 injuries/1000h of exposure). Despite the inherent risks, extreme sports have gained popularity in recent decades, involving both elite and recreational athletes (6).

From a psychological point of view, recent research suggests that extreme sport participants are not one homogenous group of risk-takers driven by their desire for thrill (7–9). Rather, motives for extreme sport participation differ between the activities (10). Some extreme sport participants, such as skydivers, seem motivated by the sensations of the activities, whereas mountaineers may be motivated by the agentic and emotion-regulating effects of their activity (10). The difference might occur due to the differing demands of each activity. Skydiving is brief and intense but easily accessible, whereas mountaineering requires extended periods of physical exertion and has high barriers to entry.

A DMB race is reported to be between 2-5 minutes (11). Since the activity it is short in duration and easily accessible (especially for those who travel up the mountain via cable car), it could, therefore, be categorized as a thrill-seeking activity. Important variables that influence downhill performance are, in decreasing order of importance; rider skill, handgrip endurance, self-confidence and aerobic capacity (11). Many extreme sport activities can be carried out at varying levels of difficulty (12). In DMB, trails vary in steepness, narrowness, turn radius and trail condition, requiring higher skills of the riders on more difficult trails. Since rider skill is the most influential variable on downhill performance, the aim of this study was to propose a new approach for studying participation variables and outcomes in a specific discipline, depending on the rider skill level of participants.

METHODS

Trail categorization

Trails were categorized using the Mountain bike Trail Difficulty Scale (MTDS; 13) (**table I**) which ranks trail difficulty and danger based on numbers, exponents and letters according to the following equation:

$$\text{number}^{\text{exponent}}+\text{Letter}$$

The number describes the difficulty of the trail based on width gradient and quality (see Table 1 for a comparison of the two evaluated trails 4 and 8). The exponent describes the jump difficulty (^{2} = Jumps with good landings/no dangerous gaps/ small to middle heights; ^{3} = Jumps with good landings of greater heights/ necessity to jump over gaps but no greater danger; ^{4}= jumps with dangerous gaps and difficult landings but without great height). Letters ranging from B to E are used to describe the likelihood and danger of potential falls while riding the trails. A ranking of B describes trails where falls are possible from a low height into relatively safe terrain, whereas on E trails, crashes due to riding errors are likely and potentially life threatening.

Table I. Characteristics of trail category 4 and 8 by the mountain bike trail difficulty scale.

	4	8
Trail width:	narrow 0,5 to 1,5 m	narrow 0,5 to 1,5 m to extreme narrow (<0,5m)
Gradient:	middle to steep 10-20%	very steep (20-40%) to extreme steep (>40%)
Condition:	low branches, Stones, good grip	low to high branches, big Stones, extremely blocked trail
Turn radius:	narrow curves	Hairpin turns and narrow hairpin turns (necessity of moving the back wheel)

Procedure

256 downhill mountain bike riders (DMBR) were questioned at two different bike parks after finishing either an easy categorized trail (4^3 + B or 4^2 + B) or a difficult categorized trail (8^3 + B, 8 + B, or 8^4 + B). Trails were noted and integrated in the questionnaire. In the difficult trail category, a high level of skill is necessary, whereas, the easy trail could be completed without specific downhill skills. 66 DMBR only answered the first page of the questionnaire and therefore, were excluded, resulting in 190 datasets to analyze. 112 answered the questionnaire after riding an easy trail (ET) and 78 after a difficult trail (DT).

Questionnaire

The questionnaire consisted of demographic variables (age, gender), specific variables related to DMB participation (experience, frequency, accident occurrence), injury type and psychological scales. Injury type was more well-defined, to include affected body part(s). The psychological scales included the Sensation Seeking, Emotion Regulation and Agency Scale (SEAS (10)), the Risk-Taking Inventory (RTI(14)) and the Risk-Taking Behaviour Scale (RBS-K(15)).

The SEAS 'While–inventory' evaluates the experience of sensation seeking, emotion regulation and agency while participating (10). The German Version (G-SEAS (16)) consists of 14-items and is rated on a 7-point Likert scale. Good internal consistency and a correlation with established measures of sensation seeking, emotion regulation and agency was shown (10, 16).

The RTI measures risk-taking in high-risk sports across two opposing factors: deliberate risk-taking (DRT, three items) and precautionary behaviors (PB, four items). They are measured on a seven item, five-point Likert-scale—ranging from one (never) to five (always) (14). The German version (G-RTI; (16)) showed a good model fit and internal consistency.

As a further indicator of risk-taking behavior, the German version of the RBS-K (17) was used. It is a three items scale scored on a 5-point Likert scale—ranging from one (strongly disagree) to five (strongly agree). This scale allows classification of the participants into risk-prone (total mean + standard deviation) and risk-averse people (total mean – standard deviation). All participants in between this range are defined as neutral. Internal consistency was shown across different language versions (15, 18, 17).

Statistical analyses

Data are presented as means and standard deviations, and as absolute and relative frequencies. Chi-square tests and Mann-Whitney U tests were used to calculate differences between the groups of DT riders and ET riders. The analysis was done using IBM SPSS Statistics 23.0. All p-values were two-tailed and values of $p < 0.05$ were considered to indicate statistical significance.

RESULTS

In total, the population consisted of 26.7% females and 72.3% males, with a mean age of 31.12 ±8.56 years and a mean experience of 8.04 ±7.41 years in DMB. The majority (58%) of the sample population participate two to three days per week in their activity, 25.2% participate once per week and 16.3% participate more than 4 days per week. Comparing both cohorts, there was a significant difference in age and gender alike. Younger people and fewer women rode the more difficult trails (**table II**). Additionally, DT riders had more experience and higher riding frequency. Almost half of DMBR experienced an accident (n=98), with no significant difference seen between the groups: 43.9% of ET riders and 57.8% of DT riders. The majority of accidents were reported to be due to the rider's own fault. Only two subjects reported an accident due to another rider's fault. Very few riders who experienced an accident (16% ET and 52% DT) could recall their injury type and location. The majority of reported injuries were contusions and abrasions (ET: 5, 71%; DT, 21, 84%). DT riders differed in bone fractures (ET 1, 14%; DT: 9, 36%). Three of DT riders reported craniocerebral trauma and one of DT riders reported a spinal cord injury. Injury locations were similarly distributed on upper and lower extremity, and injuries to the internal organs were reported by one person of each cohort.

In terms of protection equipment, all but one person (ET) reported riding with a helmet. Every DT participant noted

Table II. Demographics.

	Easy Trail (n=114)	Difficult Trail (n=83)	Significance
Age	32.24 (9.26)	29.48 (8.71)	.039*[b]
Gender	female: 38 (33.6%) male: 75 (66.4%)	female: 15 (18.1%) male: 68 (81.9%)	.015*[a]
Experience [years]	7.48 (7.62)	8.71 (7.10)	.029*[b]
Frequency [1/week]	37 (32.5%)	13 (15.7%)	.025*[a]
[2-3/week]	61 (53.5%)	53 (63.9%)	
[>4/week]	16 (14%)	17 (20.5%)	
No Accident	64 (56.1%)	35 (42.2%)	.162[a]
1 accident	20 (17.5%)	14 (16.9%)	
2 accidents	13 (11.4%)	16 (19.3%)	
>2 accidents	17 (14.9%)	18 (21.7%)	
Third party responsibility	2 (4.0%)	0 (0.0%)	.342[a]
Own responsibility	43 (86.0%)	45 (91.8%)	
Both	5 (10.0%)	4 (8.2%)	

Note: *p<.05, [a] Chi-square analyses, [b]Mann-Whitney-U Test, numbers are presented as means ± standard deviation or absolute and relative frequencies.

wearing a helmet and most frequently, gloves, knee protection and back protection (**table III**). A neck brace was reported by 4% of both cohorts. The choice of shoes did not make a difference between the cohorts. A significantly higher use of back protection and knee protection was seen in DT riders compared to ET riders.

DT riders had higher deliberate risk-taking and higher sensation-seeking scores than ET riders (**table IV**). DT riders perceived their sport as more dangerous than ET riders. There was also a significant difference in the experience of sensations between both cohorts. Precautionary Behavior, Agency and Emotion Regulation did not differ between the groups. The group of risk-averse rider was smaller in DT than ET, however, there was no statistical significance.

DISCUSSION

The aim of the study was to assess DMBR of easy and difficult trails. ET and DT riders differed significantly in demographic variables, safety equipment and psychological outcomes. Accident occurrence did not differ between ET riders and DT riders. Although a minority of those who experienced an accident made a detailed statement to injury type and affected body part, it seems that DT riders endured more serious injuries (bone fracture, craniocerebral trauma). More serious injuries, such as fractures, were also reported by DMB World Cup athletes compared to recreational athletes (5). Since the difficult trails are more challenging (see comparison in methods), it is possible that faults within this difficulty have more serious consequences for DMBR. Comparing DT riders and ET riders in the present study with recre-

Table III. Protection equipment used at the time of the survey.

Type of Protection	Easy Trail	Difficult Trail	Significance
MTB helmet	58 (51%)	33 (40%)	.122
Full-face helmet	54 (47%)	51 (60%)	.051
Goggle	80 (70%)	63 (76%)	.373
Gloves	99 (87%)	75 (90%)	.448
Protection jacket	24 (21%)	11 (13%)	.157
Knee protection	87 (76%)	80 (96%)	<.001**
Elbow protection	42 (37%)	36 (43%)	.355
Back protection (incl. Backpack)	62 (54%)	68 (82%)	<.001**
Klickshoes	28 (25%)	21 (25%)	.124
Mountainbike shoes	63 (55%)	54 (65%)	
Regular shoes	23 (20%)	8 (10%)	

Note: numbers are presented as absolute and relative frequencies *p<.05,**p<.01.

Table IV. Psychological outcomes.

Psychological Outcomes	Easy Trail	Difficult Trail	Significance
DRT	2.69 (.12)	3.40 (.15)	.001 [b]**
PB	4.83 (.12)	4.95 (.15)	.358 [b]
SEAS_SS	4.55 (.12)	5.01 (.12)	.009 [b] **
SEAS_ER	4.35 (.13)	4.62 (.15)	.134 [b]
SEAS_AG	5.64 (.08)	5.72 (.09)	.313 [b]
RBS risk-loving	18 (15.8%)	16 (19.3%)	.533 [a]
RBS risk-averse	23 (20.2%)	12 (14.5%)	
RBS neutral	73 (64.0%)	55 (66.3%)	
Perception of difficulty (1 = not dangerous, 7 very dangerous)	3.89 (.11)	4.26 (.13)	.043* b

Note: psychological outcomes **p<.01, *p<.05, DRT deliberate risk-taking, PB precautionary behaviour, SEAS_SS Sensation Seeking, SEAS_ER Emotion Regulation, SEAS_AG Agency, RBS risk-taking behaviour scale, [a] Chi-square analyses, [b]Mann-Whitney-U Test.

ational DMB and DMB World Cup Athletes of Himmelreich (5), showed the more skilled rider cohort (DT riders and DMB World Cup Athletes) were younger and had a higher riding frequency than both of the other cohorts. However, the cohorts of DT riders and DMB World Cup Athletes by Himmelreich (5) differ in their age (DT: 29.5 years vs 23.1 years). When setting the injury occurrence in proportion to exposure time, the difference in injuries between the cohorts of recreational and professional DMBR was only minor (5). In the present study, DT riders had significantly higher experience in their sport and higher riding frequency per week, thus higher exposure time in DMB. Compared to the cohort of Becker et al. (2013) (2), the participants of the present study had higher experience in DMB (>7 years vs 4 years). In terms of protection equipment, all but one person wore at least a helmet. Becker et al. (2013) (2) reported that 96% of all riders wore full face helmets, and in the present study, those were only 47% of ET riders and 61% of DT riders. A neck brace was only worn by 8 people in the present study compared to 34% in the population by Becker et al. (2). There was also a significant difference between ET and DT riders using back protection and knee protection, with higher usage in DT riders.

DT riders perceived their sport as more dangerous compared to ET riders. DT riders had a significantly higher use of protection equipment than ET riders, but also had a higher score in deliberate risk-taking. Freeriders reported to have changed their behaviour after experiencing an accident or close call towards higher precautionary behavior (9), but a difference in the assessment of precautionary behavior was not seen between ET riders and DT riders. However, the usage of higher knee and back protection could be interpreted as a higher precautionary behavior in terms of protection equipment. With data showing that DT riders experience more serious injuries, the experience of injuries might lead to a different realization of the risks involved and thus, a different perception of the dangerousness of the sport.

The experience of thrill during the activity differed significantly between the cohorts in the present study. In previous studies, sensation-seeking means were higher in freeriders (7) and both mountaineers and skydivers (10) than they were in DMBR of the present study. However, the experience of Agency showed comparable means to the cohorts of freeriders and both mountaineers and skydivers (7, 10). Since no control group was assessed, it cannot be concluded if DMB is a thrill-seeking activity. However, DT riders experienced higher sensations throughout the activity and reported to take more deliberate risks. Sensation-seeking and deliberate risk-taking have shown to be positively related in previous studies (16, 14).

A difference in the categorization of DT riders and ET riders as risk-loving and risk-averse persons was not seen. The vast majority of all accidents were reported to be due to the rider's own fault without any third-party responsibilities. This is comparable to Becker et al. (2) who reported rider's fault as the most common fault for accident occurrence. Although DT riders perceive their sport as dangerous and more dangerous than ET riders, prevention strategies in terms of risk-assessment capabilities could be implemented. Protection equipment use was high in the present study and was reported to be especially high in young mountain bikers (19). Craniocerebral Trauma was surprisingly low in the present study compared to other studies (2, 5), which might have been prevented with the use of protection equipment.

Strength and limitations

This study used a unique cohort since, within an extreme sport activity (a mountain bike sub-discipline) to differentiate difficulty levels after a trail was completed. Being that it is difficult to classify many extreme sports, the results of this study's methods may serve in the future to differentiate other adventure or extreme sports based on their conceptualization. (12). Although experience was assessed, no conclusions could be drawn towards injuries per hour. With a mean experience of 7 years, ET riders still showed higher experience compared to prior studies in DMB. Only 16% of ET riders and 52% of DT riders who experienced an accident with medical treatment could recall injury type and location. Accident occurrence was not limited to a time frame, and no information of time of accident or injury occurrence was asked. Although participants were questioned in the bike park after completion of their trails, data of injuries and accidents were collected retrospectively on previous accidents/injuries within the last years. Questionnaires were self-evaluated and no medical assistance for classifying injuries was provided. The retrospective nature of many studies on extreme sports is a common problem (20), and they are also limited by recall bias (2). Since no control group was assessed no conclusions can be drawn towards low-risk sports.

CONCLUSIONS

This study focused on a specific sub-discipline of mountain biking and used a unique cohort of DMB riders from easy and difficult trails. Accident occurrence did not differ significantly between the cohorts. However, DMB riders of difficult trails scored higher on deliberate risk-taking measurements and perceived their sport as more dangerous than DMB riders of easy trails. The vast majority of accidents are reported as one's own fault with an even higher self-responsibility and injury rate in DMB riders of difficult trails. Since those riders also wore significantly more protection equipment, preventive steps for higher skilled riders should include steps towards a better risk-assessment capability. The right use of protection equipment should be explained to all DMB riders, but especially targeted for DMB riders of easier trails.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (21).

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ORIGINAL ARTICLE

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Hand-arm vibration in motocross: measurement and mitigation actions

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SUMMARY

Objective. This study focused on the quantification of vibration which reaches the hands of motocross riders and on the reduction of such vibration thanks to the handlebar and handlebar mounts.

Background. Vibration transmitted through the hand and arm can lead to vascular and musculoskeletal problems that are well documented in the scientific literature. Controlled studies identifying plate-handlebar characteristics effects on the vibration attenuation in motocross are lacking.

Methods. We measured the vibration exposure of professional and recreational motocross riders on a motocross track and replicated the vibration patterns on a LDS V930 shaker in the laboratory, to analyze the effectiveness of various components in reducing the rider vibration exposure. Laboratory tests were performed with ten subjects randomly gripping different combinations of handlebars and steering plates, and questionnaires were used to evaluate the comfort. Objective measurements of vibration reduction were then compared to the subjective values of perceived comfort.

Results. According to the current EU legislation, the measured vibration levels reach the exposure limit in less than 1h. The mechanical characteristics of the handlebars and steering plates have a limited effect on the vibration transmitted to the rider's hands. The rubber elements that many manufacturers use to reduce the vibration have limited effects at frequencies that are harmful for the musculoskeletal system. Questionnaires results have no correlation with the measured plate and handlebar performances.

Conclusions. Most of the techniques used to reduce the hand-arm vibration exposure of motocross drivers are ineffective.

KEY WORDS

Hand-Arm vibrations; transmissibility, riding comfort, steering plate, handlebar, steering system, handlebar's grip, motocross

INTRODUCTION

Ground vehicles' manufacturers put a lot of effort into increasing driving comfort, mainly reducing the vibration energy introduced by road irregularity and transferred to the human body. High levels of vibration do not only generate discomfort, but as documented in the scientific literature, they are also strongly correlated to musculoskeletal disorders. A prolonged exposure to hand-arm vibration (HAV) can lead to several disorders, known as hand-arm vibration syndrome (HAVS) (Poole et al. 2016). HAVS includes neurological, vascular and musculoskeletal injuries. Neurological damage due to vibration exposure is irreversible and can result in finger numbness and tingling, as well as a reduction in tactile perception and of the temperature sensitivity. The vascular damage caused by impaired blood circulation in the fingers (M. Bovenzi 1998) often results in temporary blanching (vibration white finger, VWF), during which fingers feel numb. The blanching is temporary, but the reestablishment of blood circulation is painful. In the most severe cases, the blood circulation impairment is permanent and requires finger amputation. Vibration may also lead to musculoskeletal injuries (arthritis, tendinitis and muscle fibers modification) which decrease grip force, reduce hand mobility and cause diffused pain in the entire hand and arm system. The possibility of developing HAV related injuries depends on the vibration magnitude and on the exposure time. Type of injury (neurological, vascular and musculoskeletal) however, depends on the frequency of the vibration (M. Bovenzi 1998, Hangberg 2002). Low-frequency vibration exposure mainly leads to osteoarthrosis in the elbow, wrist and acromioclavicular joint. Impacts with high-energy transfer to the hands often result in musculoskeletal disorders. These disorders are usually more severe in the presence of static joint loading. Finally, high frequency vibration increases the risk of vascular diseases (Farkkila et al. 1979, M. Bovenzi 1998). Epidemiological studies pointed out a discrepancy between the risk for VWF and that predicted by the ISO 5349 standard. This suggested that the w_h ISO weighting curve may be inappropriate for assessing the vibration-induced vascular effects (Bovenzi 1998).

Effects of vibration on the hand-arm system

There is clinical and epidemiologic evidence that symptoms and signs of VWF may be reversible after the reduction or cessation of vibration exposure, but the reversibility of VWF is inversely related to age, the duration of exposure, and the severity of the disorder at the time the vibration exposure ceases (Bovenzi, 1998). Regarding the neurologic component of HAV syndrome, there is epidemiological evidence for occurrence of loss of manual dexterity, deterioration of finger tactile perception, digital numbness and paranesthesia in occupational groups exposed to hand-transmitted vibration (Violante et al. 2000). It has been reported that unmyelinated C-fibers and thin myelinated A-δ nerve fibers, which mediate the perception of temperature can be damaged by occupational exposure to hand-transmitted vibration (Hirosawa et al. 1992).

Clinical and epidemiological data have revealed an increase in thermal and vibrotactile perception thresholds of fingertips with increasing daily vibration exposure, duration of exposure, or lifetime cumulative vibration dose (Lundström et al. 1999, Bovenzi et al. 2011, Lindsell & Griffin 1998, Ye & Griffin 2018). According to Bovenzi (1998) the osteoarticular component is a controversial matter, because early radiology investigations revealed a high prevalence of bone vacuoles and cysts in the hands and wrists of vibration-exposed workers, but later studies showed no significant increase with respect to control groups made up of manual worker.

The European Union adopted a Directive in 2002 (Directive 2002/44/EC) on the minimum requirements for the health and safety of workers exposed to vibration. The Directive introduces exposure action and limit values for both hand-arm and whole-body vibration: the Exposure Action Value (EAV) is the daily amount of vibration above which employers are required to take action to limit the exposure itself, and for HAV is 2.5 m/s^2 (daily exposure, weighted RMS acceleration level). The Exposure Limit Value (ELV) is the maximum amount of vibration an employee may be exposed to on any single day; the value should never be exceeded, as exposure to vibration levels larger than ELV is associated with high risk of developing HAVS.

HAV and WBV Exposure in road Vehicles

The literature about HAV exposure of motorcycle riders is limited Industrial Industries Advisory Council (April 2017). The first studies on the side effects of hand-arm vibration applied to motorcycles date back to 1997. Mirbod et al. (1997) performed a study that aimed to evaluate subjective symptoms in the hand-arm system of all traffic police motorcyclists of a Japanese city. The secondary output of their study was to assess the hand-arm vibration exposure associated with their daily tasks. The first objective has been fulfilled by means of a questionnaire submitted to 150 persons, in which information about the occupational history and the presence of subjective symptoms in the hand-arm system was collected. This survey revealed that the most significant riding side effect is shoulder stiffness, as almost one officer out of two suffered from this symptom. Authors concluded that finger numbness, finger stiffness, shoulder pain were common among the police drivers. The measured handlebar vibration (measured according to the ISO 5349 standard) was 2.8 – 4.5 m/s^2 (8 hours equivalent). The subjects with larger vibration dose showed significantly higher prevalence of symptoms in the fingers and shoulders in comparison with the control group. A similar analysis was carried out by Shivakumara and Sridhar in 2010. The work focused on the study of the vibration effect on the driver and the measurement of the magnitudes of vibration in motorcycles. The authors considered both HAV and whole-body vibrations (WBV). The experimental activity showed that the HAV level exceeded ELV, as 8 hours of work lead to a HAV exposure level of 4.8-7.6 m/s^2.

Astöm et al. (2006) studied the HAVS and musculoskeletal symptoms in the neck and the upper limbs in professional drivers of terrain vehicles. They asked a group of almost 800 professional drivers of forest machines, snowmobiles, snow-groomers and reindeer herder, and a group of almost 300 randomly selected males to complete a questionnaire about HAVS' symptoms and musculoskeletal symptoms in the neck and the upper limbs. The analysis of the questionnaire showed that there is a relation between exposure to driving terrain vehicles and some of the HAVS' symptoms. Moreover, increased odds of musculoskeletal symptoms in the neck, shoulders and wrists were also found, and it seemed to be related to the cumulative exposure time.

The number of studies related to the motocross is more limited. Grange (2009) and Humpherys (2018) evidenced that there is a large prevalence of chronic exertional compartment syndrome in motocross drivers; riders often refer to the forearm pain as "arm pump" that results in a decrease in riders' performance and may force the riders to stop driving. The orthopedic literature offers little information regarding evaluation and treatment of this pathology. Symptoms are similar to those of HAVS and can be due to variations of the blood flow to the muscles in the forearm combined with relatively decreased venous outflow and to the vasoconstrictor effect of the vibration (Simões et al. 2016, Ascensao et al. 2007).

Scope of the work

The literature review evidences that there is a lack of knowledge on the vibration exposure of motocross drivers and on the effect that different materials have on the vibration transmitted to riders. The present study aims to quantify the vibration exposure of professional and recreational motocross drivers, and to identify the best combination between handlebar and steering plate to reduce the vibration transmitted to the rider'shands.

MATERIALS AND METHODS

Preliminary motocross track tests focused on the quantification of the vibration exposure of professional and recreational motocross drivers. Subsequently, in order to identify the best combination between handlebar and steering plate to reduce the vibration transmitted to the rider's hands, the vibrations measured in track tests were experimentally reproduced in the laboratory. The effectiveness of the different solutions was assessed both by objective evaluations (vibration measured on the subject hand) and on subjective comfort evaluation (based on questionnaires results).

Motocross track tests

Different tests were performed on a single track. Two types of 4-stroke motorcycles were driven by two drivers: 1) KTM EXC 350 F driven by an amateur driver; the second is a Honda 450 CRF cross driven by a professional driver. Motorcycle 2 was tested in two different sessions characterized by different track and traffic conditions. The measurement method was similar to the one used in other sports applications by Tarabini et al. (2015). Both motorcycles were instrumented with a triaxial accelerometer (PCB 356 A21) on the steering plate, measuring the accelerations along three directions x (fore and aft), y (medio-lateral) and z (almost vertical, aligned with the fork direction) while a single-axis accelerometer Endevco 27 F11 was located close to the throttle, measuring the vibration along the z axis. This configuration neglected the high frequency attenuation provided by the grips and the gloves, that were characterized in dedicated laboratory tests. Data were sampled by a NI 9234 acquisition board that was stored in a specifically designed case fixed on the lower and upper plates, in place of the number board (**figure 1**). A miniaturized personal computer, located in a backpack, sampled the data that were analyzed offline.

The parameters used to quantify the vibration exposure are the weighted levels of vibration along three mutually perpendicular axes, according to the ISO 5349 standard. The accelerations measured by the two vibration pickups shown in **figure 1** (x_1, y_1, z_1, z_2) were frequency-weighted using the w_h curve ($x_{1,w}$, $y_{1,w}$, $z_{1,w}$, $z_{2,w}$) and then used for the computation of the weighted level of vibration (RMS of the weighted vibration along each axis, $a_{x1,w}$, $a_{y1,w}$, $a_{z1,w}$, $a_{z2,w}$). The parameter used for the quantification of the driver risk is the vector sum of the magnitude of vibration (a_v), computed in accordance with the ISO 5349. In addition, the daily vibration exposure A(8), computed according to

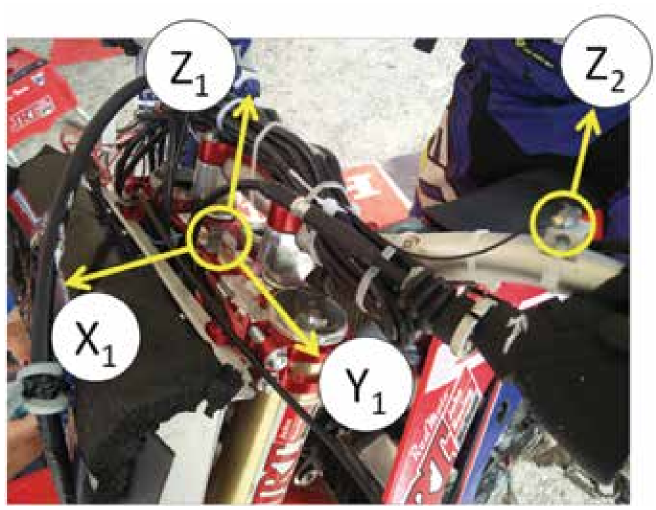


Figure 1. Position of the accelerometers in track tests and orientation of the measurement axes.

the ISO 5349 standard, has been evaluated considering one hour of activity each day (typical of professional drivers) as well as the time to reach the exposure action and limit values (EAV and ELV, 2.5 and 5 m/s^2 respectively as defined in the Directive 2002/44/EC of the European Parliament and of the Council). With the aim of assessing the danger of vibration to the vascular, musculoskeletal and neurological systems, the vibration spectra have been analyzed similarly to what was done in existing literature studies (Alberti, et al. 2006) and as suggested by the ISO 5349 standard in presence of repeated shocks.

Laboratory tests

To select which handlebar components would be tested, the two motocross riders were asked to suggest readily available commercial components which, to their knowledge, incorporate some form or anti-vibration features/materials. The riders identified 3 handlebars and 4 steering plates, and the parts were chosen accordingly. Handlebars 1 and 3 incorporated rubber elements, while handlebar 2 was rigid. All the steering plates incorporated rubber or anti-vibration elements; the steering plate C and the handlebar 1 were provided by the manufacturer with rubber elements of varying stiffness; in these cases, a subscript was used to indicate which rubber element was chosen and to characterize the stiffness. Handlebars and steering plates are shown in **figure 2** and **figure 3** respectively.

Handlebars were labeled 1r, 1y, 1b (handlebar 1 with red, yellow or blue rubber), 2 and 3; in the formulas, the subscript h was used to identify the quantity referring to a specific handlebar (being h an integer number between 1 and 5). Steering plates were labeled A, B, Cw, Cg (handlebar 1 with white or green) and D; in the formulas, the subscript p was used to identify the quantity referring to a specific steering plate (being p an integer number between 1 and 4). All the combinations of plates and handlebars were mounted on a vibration generator (LDS V830, maximum stroke ±25 mm) which reproduced the vibration measured on the track test in the most severe configuration. Volunteers gripped the handlebar trying to reproduce the typical motocross driver posture. Steering plate vibrations along the x and z direction were measured using two piezoelectric accelerometers (Endevco 27A11); the handlebar vibration in correspondence of the hand was measured using a piezoelectric tri-axial accelerometer (PCB 356B21). The experimental setup is shown in in the upper part of **figure 4.**

SUBJECTS AND METHODS

Ten volunteers tested all the 20 plate-handlebar combinations; i is used to indicate tests performed by each volunteer, each volunteer completed the tests in less than 2 hours, including the time required for changing the experimental setup (duration of data acquisition for each configuration

Figure 2. Tested handlebars.

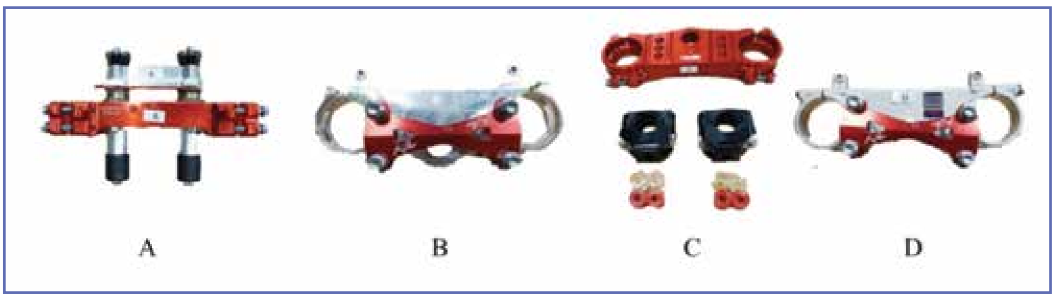


Figure 3.Tested steering plates.

120 s). The vibration exposure in our tests was lower than the EAV and consequently the risk for the participants was negligible. All the volunteers gave their written consent to the study, which met the current ethical guidelines in sports. Exclusion criteria were moderate or severe upper limb injuries in the 6 months preceding the assessment and diabetes. The effectiveness of the different combinations was quantified by the vibration measured at the handlebar ($a_{p,h,i}$) which was obtained (under the hypothesis of system linearity) by multiplying the track w_h weighted acceleration spectrum times the transmissibility.

After each test, participants were asked to report their level of discomfort $D_{p,h,i}$ for the plate p and the handlebar h on a 0-9 scale. Marks were normalized ($d_{p,h,i}$) by subtracting the average discomfort μ_i reported by the participant for all the handlebars and plates and dividing the difference by the standard deviation σ_i of data reported by the same participant, similarly to what was done in similar literature studies (Tarabini 2018, Dickey 2007).

$$\mu_i = \frac{1}{20}\sum_{p=1}^{4}\sum_{h=1}^{5} D_{p,h,i}$$

$$\sigma_i = \sqrt{\frac{1}{20}\sum_{p=1}^{4}\sum_{h=1}^{5}\left(D_{p,h,i} - \mu_i\right)^2}$$

$$d_{p,h,i} = \frac{D_{p,h,i} - \mu_i}{\sigma_i}$$

The average discomfort for each plate-handlebar combination was computed starting from the normalized discomforts reported by each of the i-th subjects as follows:

$$\overline{d_{p,h}} = \frac{1}{10}\sum_{i=1}^{10} d_{p,h,i}$$

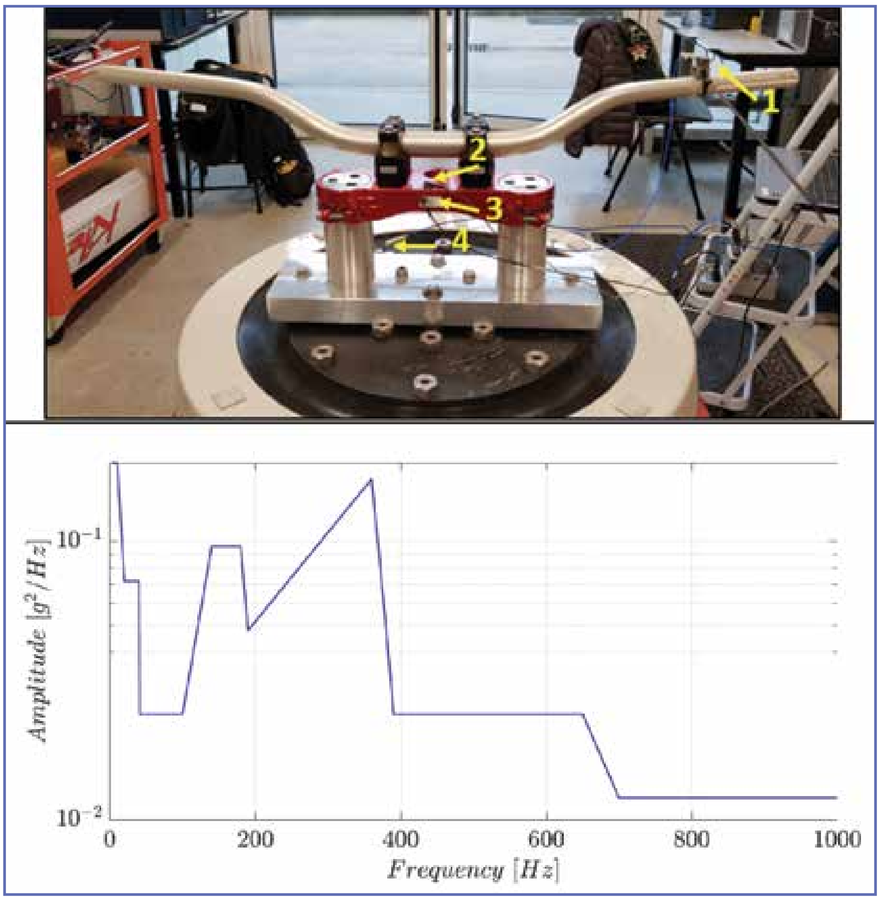


Figure 4. On the top the experimental setup with accelerometers located on the handle (1), on the steering plate along vertical and horizontal vibration (2 and 3) and on the shaker head (4). On the bottom, shaker input power spectral density.

RESULTS

Track tests

The time histories of the vibration measured during the track tests are shown in **figure 5**.
The vibration levels (weighted and unweighted) measured in the different experimental sessions along the three axes are summarized in **table I**. Results show that after 1 hour of activity, the exposure is systematically larger than the EAV (2.5 m/s^2). In the most critical situation (Motorcycle 2, session S3), the limit value is reached after 0.9 h (54 minutes), thus indicating that the continuous exposure to hand-arm vibration might lead to the set of disorders indicated as HAVS.
Given that the vibration frequency content heavily influences the disorder that the riders might develop, the short-time Fourier transform (STFT) of the vibration (i.e. the evolution of vibration frequency with respect to time) has been analyzed. **Figure 6** shows the STFT of the vibration along the z axis shown in **figure 5 (a)**. The spectrogram shows the clear presence of three different vibration components. The vibration between 0 and 20 Hz are the ones generated by the road irregularities and jumps. The components between 100 and 400 Hz are the vibrations generated by the 4-stroke engine, while the components above 400 Hz (with the smaller amplitude) are reasonably due to structural vibration.
The vibration level along the z axis obtained in laboratory test with the different plate-handlebar combinations are summarized in **figure 7**. The plot shows that the effect of the materials is minor, as the vibration levels are close to 12 m/s^2 (i.e. the value imposed on the shaker head) for all the considered configurations.
The substantial equivalence between all the tested solutions is confirmed by the questionnaires' result, as the differences between the average discomfort ($\overline{d_{p,h}}$) for each combination of plate p and handlebar h (shown in **figure 8**) are small in comparison with the data dispersion. The plot shows that the Plate A and handlebar 2 was the combination which had the lowest mean discomfort. In this configuration, the

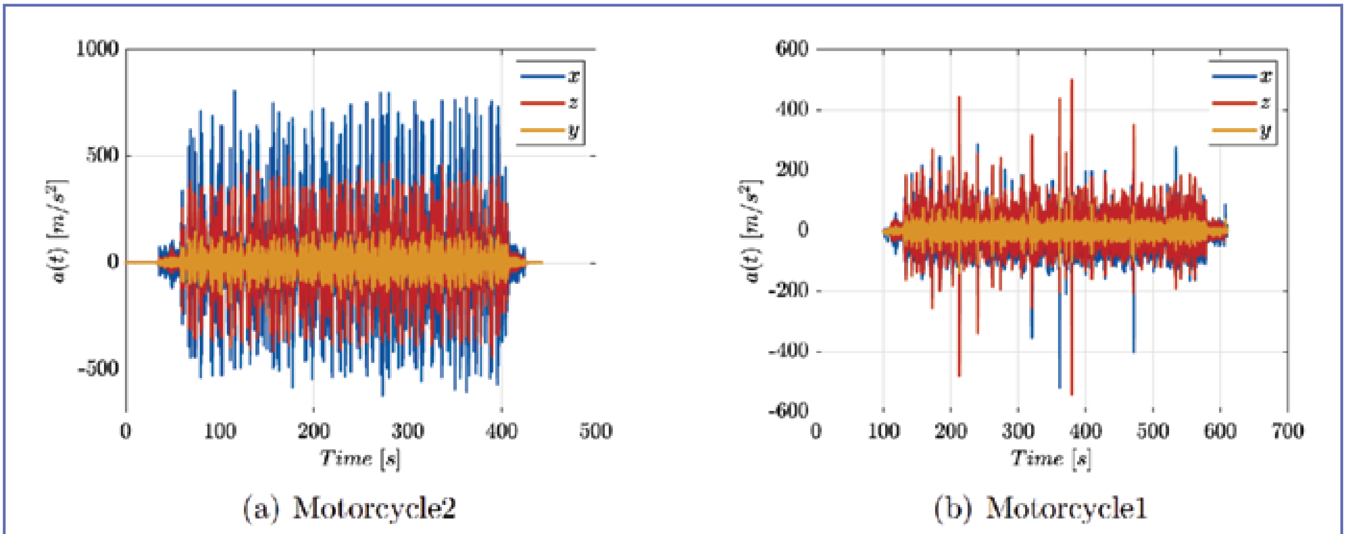


Figure 5. Time histories of the vibration measured at the steering plate for the motorcycle 1 (a) and 2 (b).

Table I. Unweighted vibration levels (x, y and z) and weighted vibration levels (awx, awy and awz) and exposure level after 1 hour of activity measured in the different experimental sessions at the steering plate. The last two columns indicate the time after which the exposure limit value and action values are reached.

Motorcycle	Session	x	y	z	a wx	a wy	a wz	a(8), T=1h	T (ELV)	T(EAV)
		(m/s² RMS)	(m/s² RMS)	(m/s² RMS)	(m/s² RMS)	(m/s² RMS)	(m/s² RMS)	(m/s² RMS)	h	min
1	S1	24.4	7.5	25.7	5.0	2.3	8.1	3.5	2.1	31
2	S2	60.9	14.7	52.2	5.8	3.4	9.4	4.1	1.5	22
2	S3	83.9	17.8	66.7	8.0	4.1	12.0	5.3	0.9	13

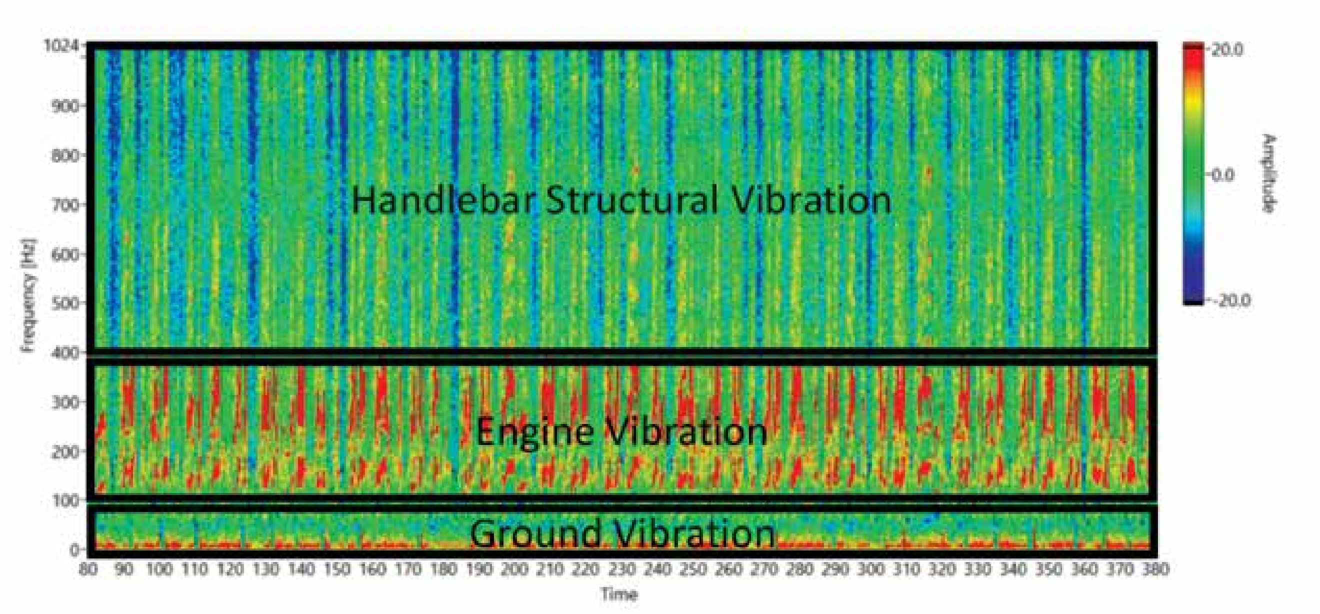
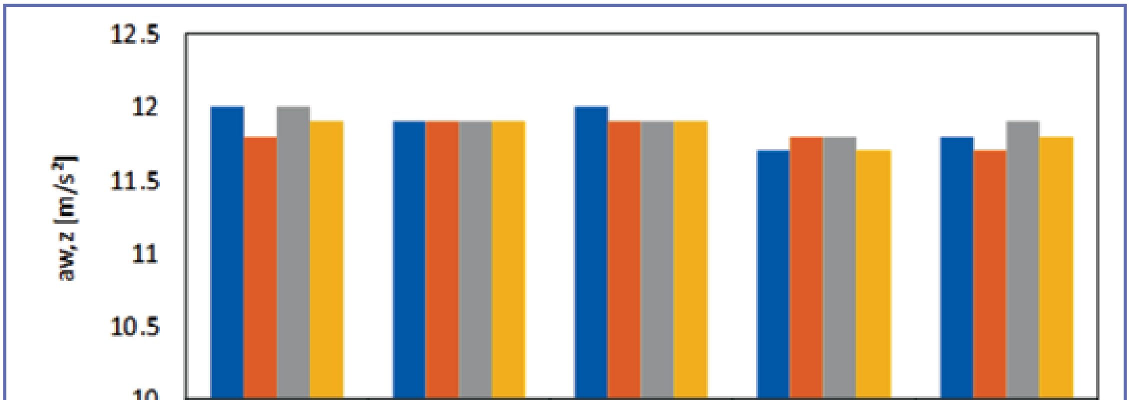


Figure 6. Short-time Fourier Transform of the vibration measured at the steering plate Plate-handlebar test.



	Handlebar 1r	Handlebar 1g	Handlebar 1b	Handlebar 2	Handlebar 3
Plate A	12	11.9	12	11.7	11.8
Plate B	11.8	11.9	11.9	11.8	11.7
Plate Cb	12	11.9	11.9	11.8	11.9
Plate Cv	11.9	11.9	11.9	11.7	11.8

Figure 7. Hand weighting function on the left, acquired hand weighted acceleration on the right.

measured vibration is 11.7 m/s^2. The configurations that lead to the highest discomfort are the combinations of plate Cv with handlebars 1r and 3; in these configurations the vibration levels were 11.9 and 11.8 m/s^2 respectively.

The small differences between the tested configurations was confirmed by the boxplots of the normalized discomfort categorized in different groups on the basis of the plate and handlebar, shown in **figure 9**. The graph shows that the variability of

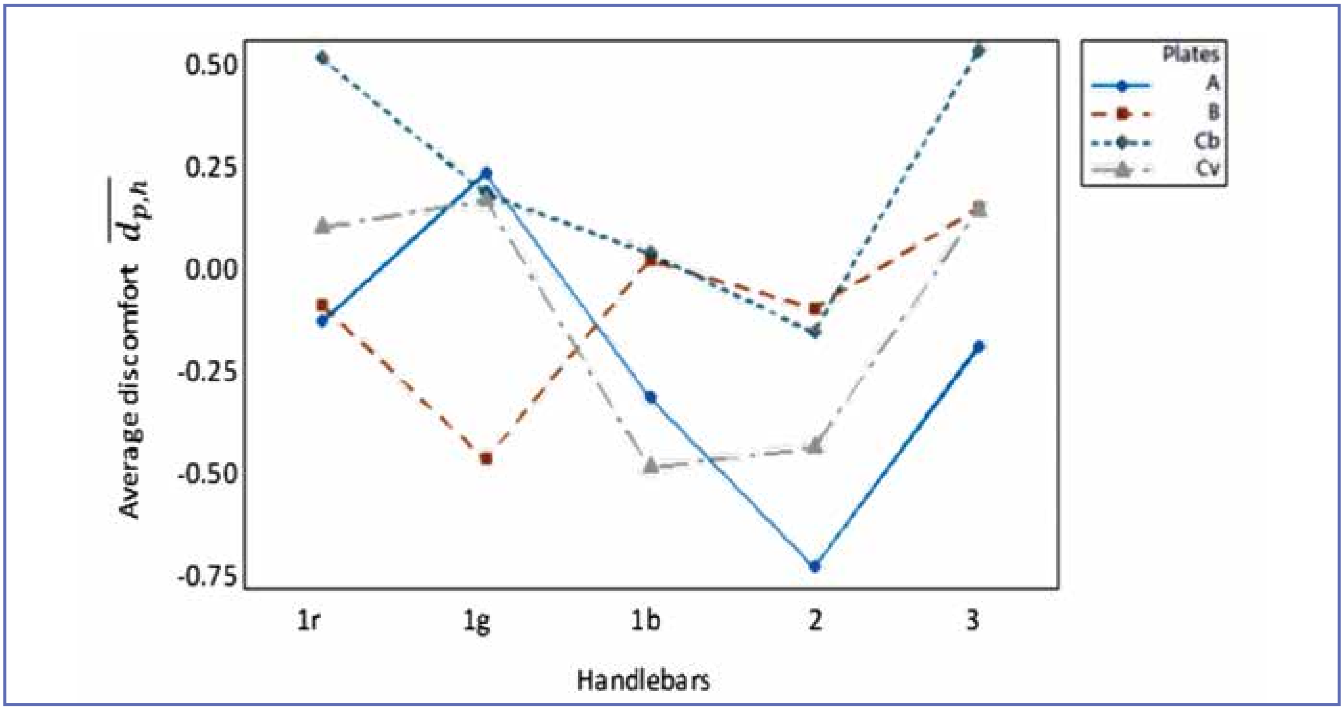


Figure 8. Average discomfort as a function of the handlebar h and plate p.

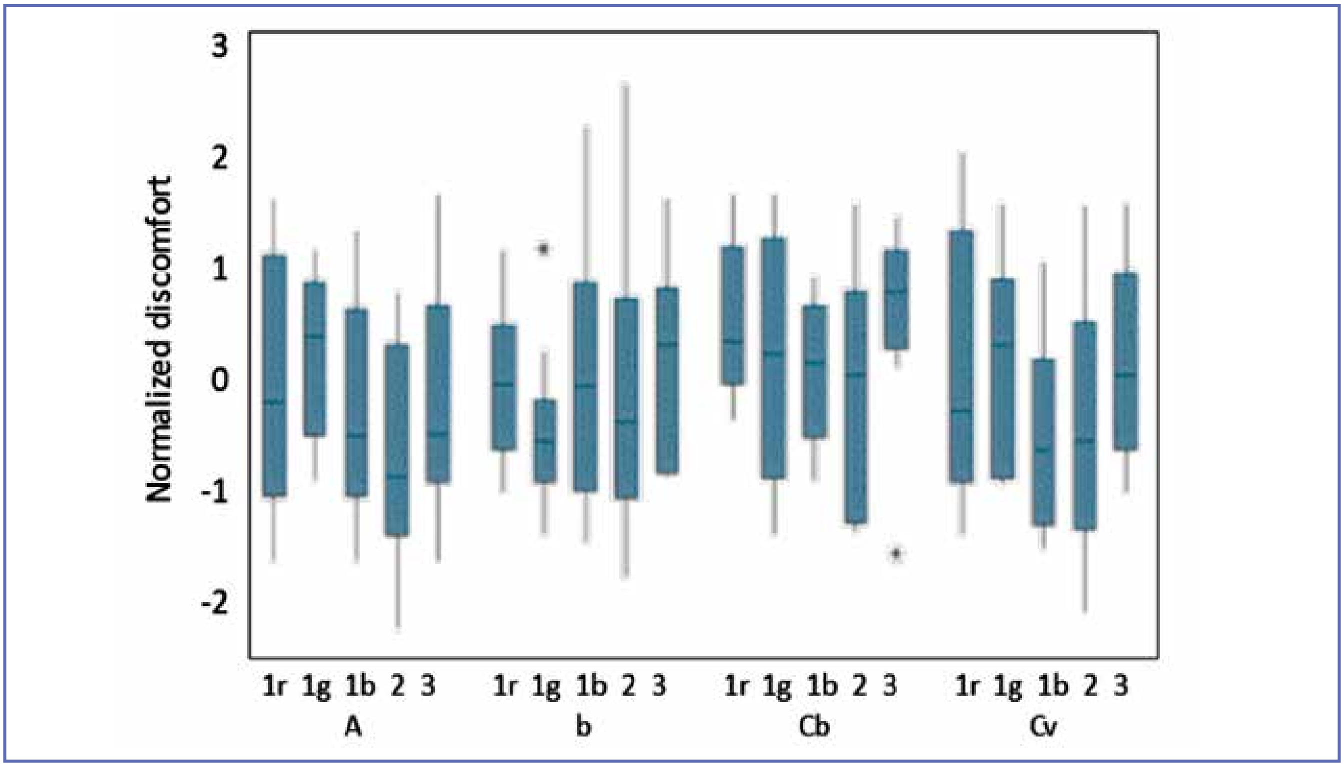


Figure 9. Boxplot of the reported discomfort for the different plates/handlebar configuration.

the discomfort reported by subjects is much larger than the difference between the average discomfort, thus evidencing that a plate-handlebar combination can be comfortable for some participants, but uncomfortable for others.

DISCUSSION

According to the current EU legislation, the vibration to which motocross riders are exposed, might lead to different disorders of the hand arm system. Results showed that the EAV can be reached in approximately 30 minutes by a recreational driver (session S1) and less than 15 minutes by a professional driver (session S3). This is consistent with the phenomenon of the arm pump (IIAV, 2017), resulting in intermittent forearm pain during and after the training period. The high vibration exposure suggests that professional motocross drivers might develop the HAVS, consistently with the existing literature studies that reported finger numbness for mailman driving motorcycles (Mirbod et al. 1997).

As reported in an information note of the Industrial Injuries Advisory Council of the United Kingdom (IIAV, 2017), the scientific literature is rather patchy, but shows that the vibration on the motorcycle's handlebar can be of sufficient magnitude to lead to HAVS. The potential for vibration on the handlebars of motocross to cause relevant HAV pathologies is even more relevant, given the magnitude of the vibration evidenced in our tests and the presence of shocks and transient events, whose adverse effect has been largely documented in the literature (Burstrom et al. 1999, Moschioni et al. 2011, Bovenzi 1998).

The spectral analyses evidenced the presence of different vibration components: the effect of the interaction between the motorcycle and the track is evident at frequencies below 20 Hz. These frequencies, according to the current scientific literature (Bovenzi 1998, Hangberg 2002), may lead to musculoskeletal disorders. The vibration coming from the engine (with frequencies between 100 and 400 Hz) might lead to the finger numbness and vascular diseases (Farkkila 1979, Bovenzi 1998).

The dominant vibration direction at low frequencies, is the vertical one; the vibration is mainly due to the track irregularities not absorbed by the suspensions. At higher frequencies, the vibration along the three axes is comparable, being generated by the engine and by the frame structural resonances.

Unfortunately, the effectiveness of the anti-vibration handlebars on the reduction of vibration is minor. Results of the laboratory tests showed that the plates and the handlebar mount transmit the entire vibration at frequencies below 200 Hz. The average attenuation between 200 and 400 Hz is usually limited, while above 400 Hz all the combinations exhibit resonances that increase the vibration transmitted to the rider. In general, the handlebars and the plates seem designed without accounting for the basic principles of anti-vibration devices and do not account for the direction of the vibration.

The structural handlebar and plate characteristics can be optimized following the approach described by Saggin et al. (2012). Preliminary results evidenced that in the case of motocross, where the vibration coming both from the ground and the engine is relevant, the anti-vibration solutions proposed by different manufacturers are equivalent. The situation might be different for enduro riders, where the dominant vibration is the one coming from the engine. In this case, the presence of compliant elements in the handlebar paired with the dominant tonal component in the vibration spectrum (constant engine regime) could improve the performances of handlebars and steering plates that incorporate soft elements with respect to the rigid ones. This consideration, although reasonable, has to be experimentally validated and could be the topic of forthcoming studies.

In general, results evidenced that the discomfort reported by the different subjects has a very poor correlation with the measured vibration exposure, thus indicating that the design of the anti-vibration solutions should be based on the vibration characteristics and on the optimization of the transfer function, and not (as currently performed) by subjective comfort evaluations.

CONCLUSIONS

Our investigations evidenced that the vibration exposure of professional motocross driversreaches EAV indicated by the Directive 2002/44/EC in approximately 20 minutes and the ELV min 1 hour. Recreational riders reached EAV and ELV in 30 minutes and 2 hours, respectively. The different handlebars mounts are not effective in the reduction of vibration. The proposed methods for reducing the vibration increase the exposure at high frequencies, thus increasing the risk of HAVS. Results presented in this work suggest that the vibration exposure of motocross drivers should be monitored and that almost all the combinations of handlebars and steering plates are equivalent from a comfort point of view.

ACKNOWLEDGEMENTS

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CONFLICT OF INTERESTS

Kite Performances provided the steering plates and the handlebars to Politecnico di Milano. There was no influence on experiments or data analyses that were performed by Politecnico di Milano.

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Review on Reported Concussion, Identification and Management in Extreme Sports

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SUMMARY

Background. As participation in extreme sports continues to grow internationally, the number of concussions sustained during these activities is predicted to increase. Due to the lack of organizational frameworks, governing rules, or regulated competitive structures, the incidence of concussion and its management specific to extreme sports athletes remains difficult to determine.

Methods. Relevant papers were screened from PubMed using a combination of terms related to extreme sports and concussion. After considering existing literature, papers that did not fit the authors' agreed-upon definition of extreme sports were excluded.

Results. Eleven manuscripts met inclusion criteria. Of the eleven, only five studies reported on more than one extreme sport while the other six were sport-specific. Three were review papers that used sport-specific data to generalize about extreme sports.

Conclusions. The results of our review indicate that the current literature available for concussion in extreme sports varies highly in study design and type of sports investigated. Due to the lack of knowledge regarding concussions in extreme sports, there needs to be an emphasis to better document and record concussion incidence in extreme sports, as well as the need to develop specific return-to-play guidelines for healthcare professionals treating extreme sports athletes.

KEY WORDS

Concussion; extreme sports medicine; mild-traumatic brain injury; sports-related concussion; post-concussive syndrome.

BACKGROUND

Concussion is a form of mild Traumatic Brain Injury (mTBI), defined as a complex pathophysiologic process induced by direct or indirect impulsive forces to the head that disrupts the brain's functions (1). Due to the deficiency of normative data for clinical tests, the absence of well-established validated biomarkers, the highly variable post-injury symptom presentation, and the lack of uniformity regarding concussion definition, concussions remain one of the most complex injuries in sports medicine to diagnose and subsequently manage (2–4). This complexity can result in difficulty in understanding the recovery process following injury, and may factor into why athletes are developing persistent post-concussion symptoms (3,5,6).

Sports-Related Concussion (SRC) has become a public health problem, with an estimated 1.6 to 3.8 million SRCs each year in the United States (7). In a recent multicenter cross-sectional study, 30.5% of athletes reported a previously undiagnosed concussion (8). Furthermore, many concussions that occur may go unrecognized or undiagnosed, leading to a potentially greater prevalence of injury. In the same multicenter study, the athletes who reported an undiagnosed concussion had higher mean Post Concussion Symptom Scale (PCSS) score and were more likely to have lost consciousness with their current injury than athletes without previously undiagnosed concussions (8). For athletes in extreme sports in particular, the prevalence and incidence of concussion has not been universally established. Some hypothesize that these athletes may be more vulnerable to sustaining a concussion due to the high forces and accelerations that occur during extreme sports, but an overview of extreme sports and brain injuries has yet to be investigated. Despite this lack in normative data across all extreme sports, there is some data on the subject. According to one recent study, concussions account for 9.4% of all injuries that reported to emergency departments in X games competitions from 2000-2011 (9). Overall, however, the epidemiological data on injuries in extreme sports are scarce (10).

The term “extreme sports” has become a widely used term to describe a variety of non-traditional sporting activities (11). Terms like “action sports” or “adventure sports” are often used as synonyms (12,13). Specifically, the definition of extreme sports encompasses a wide range of sport activities, which stem from the creative exploration of novel movement experiences and include water-sports (e.g. kitesurfing, SCUBA diving), air-sports (e.g. skydiving, paragliding) and land-sports (e.g. mountain biking, skateboarding, climbing, snowboarding, parkour). In contrast to public opinion, extreme sports cannot be considered as ‘high-risk sports’, and are not more dangerous than traditional sports, according to existing literature (14). Despite this finding, extreme sports often exploit an external source of energy, such as gravity in BASE (building, antenna, span, and earth) jumping and skydiving, or natural phenomena, such as thermal updrafts and ocean swells in paragliding and surfing, respectively. Under these circumstances, a greater prevalence of high-energy trauma cases may result from mismanaged execution during extreme sports participation (15). If applied directly or indirectly to the head, these high-energy forces may result in concussion or a more severe TBI.

The participation rate in extreme sports has grown exponentially over the last few decades, often surpassing the growth rates of many traditional sporting activities especially among children and adolescents (16–18). This growing interest has been shown by, and accredited to, the creation and increasing popularity of the X Games, the introduction of new events into the Winter Olympics, and nationally televised extreme sports events over the past decade, as described by epidemiological studies (9). Despite its expansive growth in participation rates among all ages, limited data regarding concussion prevalence exist for extreme sports. This deficiency may be attributed to the lack of organizational frameworks and regulated competitive structures during extreme sports relative to other ‘traditional’ sports (e.g. football, soccer, hockey) (19,20). As the concern for concussion and international participation in extreme sports continues to rise, a structured assessment and return to play protocol needs to be created and considered for this unique subset of athletes (19,20).

We are unaware of any published reviews on concussion incidence and management in extreme sports athletes. Therefore, the purpose of this scoping review is to examine existing studies that have assessed concussion incidence, prevalence, diagnosis, management and outcomes among extreme sports athletes. This study aims to identify gaps in the literature relating to concussion and extreme sports, in order to determine what future research is needed to improve current clinical management of brain injuries in extreme sports athletes.

METHODS

A PubMed query was completed using the key words “Extreme sport”, “Extreme environment”, “Extreme conditions”, “Action sport” and “Adventure sport”, resulting in more than 5800 papers. These results were then filtered to only include those that included patients who sustained a concussion or other head injury (e.g. mTBI, blunt head trauma). This resulted in a total of 11 papers. Of these 11, two were excluded as they did not fit the agreed upon definition of extreme sports, designed by the authors after considering existing literature: “Extreme sport is a competitive, either by comparison or self/peer evaluation, physical activity in which the participant is subjected to unusual physical and mental challenges while being exposed to environmental variables, with a risk of severe injury or fatality in the case of mismanaged execution” (14,20–22). An additional paper was also removed from the analysis because the authors did not provide a breakdown of head injuries that occurred in extreme sports specifically as compared to what was described as “other risk-taking behaviors”. Papers were also chosen using the ancestry approach in order to include anecdotal but relevant reports. This resulted in the addition of three additional pertinent papers. As a result, we reviewed 11 total studies. From each study, we extracted its design, period, number of subjects, the proportion of men and women, setting, and the rate of injuries (if applicable).

RESULTS

Of the 11 papers, only five reported on more than one extreme sport. Two of the five were reviews on the current literature, using sport-specific papers to provide insight into extreme sports literature as a whole, while the remaining three reported injury location and severity for a specific cohort. The other six papers were sport-specific, four of which were motocross-focused. Of the four motocross papers, one was a review. Most of the sport-specific papers reported injury occurrence classification except for one by Miller et al. which reflected athlete perception of their injuries and management of concussions (23). Additionally, each of the seven papers that described injury rates used data provided by emergency department visits (all but Miller et al. (23)). During analysis one study not only looked at 10 different sports, but also further divided the injuries into three tiers of risk-taking categories: extreme sports with high-risk practice, potential extreme sport and indeterminate risk, and potential extreme sports but low risk (15). In all the papers mentioned in this review, none provided a breakdown of hours of athletic exposure and how that would relate to injury occurrence rates. This breakdown could be useful for indicating if these athletes were pursuing the sport in question recreationally or competitively.

DISCUSSION

The results of our review indicate that the current literature available for concussion in extreme sports varies highly in study design and type of sports investigated. There are a few studies that report concussion occurrence rates among extreme sports athletes, which have been summarized in **table I**. Up to now, this review is the only one of which we are aware of uniting different studies and presenting concussion in extreme sports. Of the papers identified that discussed injury occurrence rates, many separated the analysis by the anatomical location (e.g. head, neck, chest, upper and lower extremity) instead of by the type of injury (e.g. concussion, laceration, contusion, fracture etc.) (15,24–26). As a result, there is a lack of concise data regarding rates of concussions alone. Furthermore, existing studies report primarily on emergency department visits and are not reflective of total injuries seen by all physicians who treat extreme sports athletes (e.g. sports medicine providers) (9,15,24–27). Within emergency departments, providers typically use templates to make the most efficient use of time. Many of these templates include specific traditional sports when assessing sport related injuries, but often use the term "other" to indicate extreme sports. As a result, if there is no written information specifically input by the health care providers idenitifying the extreme sport the data for that specific type of sport is lost (27). Additionally, of those that report on more than one extreme sport, the main focus lies on injury distribution and less on reporting current management and guidelines for return to play protocols.

Epidemiology

The majority of studies to date regarding concussions and extreme sports are sport-specific (e.g. snowboarding). In a prospective study, Nakaguchi et al. reported that 26% of all snowboard and 21% of all ski-related injuries were head injuries (28). That being said, there was no further classification to determine if these head injuries were concussions, fractures, lacerations, etc. Additionally, the data was collected from a trauma center near the most popular skiing areas in Japan, from which, it was impossible to separate those who were extreme sports athletes from those who were recreational skiers/snowboarders (28). In a separate study that reported solely on extreme sports athletes, concussion accounted for 43.9% of snowboarding injuries and 41.9% of skiing injuries (9). In an epidemiological study performed in Canada on 1332 reported snowblading, skiing and snowboarding injuries, it was observed that snowboarding related head injuries had a strikingly high incidence in beginners and during backward falling and jumping. In particular, most head injuries occurred during jumping when the surface of the ground was covered with icy packed snow (26). However, a high rate was also observed on well-marked slopes (29,30). The data concluded that snow SRCs are common and that health care professionals assessing these athletes should have increased suspicion of head injuries after a fall or collision. Educating snow sports athletes about the signs and symptoms of concussion should be emphasized to minimize under recognition and underreporting. Also, increased knowledge of concussion in these sports should include primary care providers who may be the initial contact with these patients. When considering other sports such as mountain biking, one study observed that among 494 mountain-biking injuries, concussion represented 4.6% (n=23) of all injuries (16). This rate of injury appeared to be lower than snowboarding, although the different design of the studies makes a direct comparison impossible. In a different study, concussion accounted for 29.7% of mountain biking injuries (9), thus showing the current lack of reproducibility of current concussion research in extreme sports. Mountain biking injury data may be misleading due to the lack of health care professionals located at various races or recreational rides. However, a national injury database for high school mountain biking incidents was recently implemented in the U.S., which may lead to more comprehensive and comparable data sets in the future.

Table I. Studies that investigated extreme sport athletes who sustained head injuries discovered by our PubMed query with the exclusion of reviews. TBI = Traumatic Brain Injury, LOC = Loss of Consciousness, CT = Computed Tomography, ED = Emergency Department, ES = Extreme Sport, ATV = All-Terrain Vehicle, BASE = Building, Antenna, Span and Earth.

Study	Design	Study Period	Sample (n)	Gender (M)	Aim/Purpose of Study	Rate of Injuries
Weber et al., 2018	Prospective	Jan 2002-Dec 2012	n=278 individuals with major injuries during extreme or contact sports (extreme sport only breakdown: airborne n=105, climbing n=35, skateboarding/skating n=65)	Airborne: 84.8% Climbing: 71.4% Skating: 58.5%	Sport specific injury patterns and mechanisms, to characterize individuals at risk and to identify possible approaches for prevention	Head and face injury: 38.5% Airborne 40% Climbing 49% Skating 48% Contact Sports Concussions: 9.5% Airborne 14.3% Climbing 15.4% Skating injuries
Gosteli et al., 2016	Retrospective case-series	Jan 1998-Dec 2008	n=616 injuries (219 extreme sports with high risk practice at time of injury, 69 potential ES but low risk at time of fall, 328 ES with indeterminate risk at time of fall)	70.9%	Describe epidemiology of extreme sports injuries in adults (>15 years) that required helicopter emergency medical services	High risk events: 9.1% Severe TBI, 6.9% mTBI; Snowboarding and mountain biking were specifically associated with TBI.
Sharma et al., 2013	Descriptive epidemiological study	2000-2011	n= 4,083,691 injuries (n = 381,760 head injuries, 9.3%)	Not specified	Report neck and head injuries in 7 extreme sports (snowboarding, snowmobiling, surfing, mountain biking, motocross, skateboarding, and snow skiing) at the Winter and Summer X games via national (U.S.) surveillance of emergency room visits	Concussions: 140,650 (36.8% of head injuries, 3.4% of all injuries) 43.9% Snowboarding 41.9% Snow skiing 29.7% Mountain biking 29.1% Motocross 24.6% Snowmobiling 21.9% Skateboarding 8.2% Surfing Head/neck injury: Skateboarding (highest risk) 10.21 per 10,000 person-years; Mountain bicycling (lowest risk)1.08 per 10,000 person-years
Soreide et al., 2007	Retrospective Cohort	1995-2005	n=20,850 jumps	91%	Report frequency of injuries and deaths in BASE jumping (Kjerag, Norway)	Injuries occurrence: 9.8 per 2,500 jumps; (including ankle sprains/fracture, minor head concussion, or a bruised knee)
Moroney et al., 2003	Prospective Cohort	April 1999-April 2000	n=32 (n= 6 with previous ATV experience)	71.9%	Injury prevalence in ATV-related accidents	Concussions: 6% (n=2)
Larson et al., 2009	Retrospective Case-series	2000-2007	n= 249 individuals (299 separate injury episodes)	93.2%	Injury distribution and severity in children who participated in motocross	18% LOC with 8 and 5 abnormal Glasgow Coma Scores and CT

Table I. Continues

Study	Design	Study Period	Sample (n)	Gender (M)	Aim/Purpose of Study	Rate of Injuries
Miller et al., 2016	Prospective Cohort	NR	n=782 individuals	85%	Assess concussion knowledge among amateur motocross riders	75.1% (n=587) with prior concussion history
Daniels et al., 2015	Retrospective population-based cohort	2000-2007	n=298 accidents (n=248 patients)	93.1%	Confirm the rate of head and spine injuries in the pediatric population following motocross accidents	61.2% occurred at a formal motocross course; 20% Head injuries/ TBIs; 95% LOC

As opposed to land-based sports such as snowboarding or mountain biking, during water-sports (e.g. windsurfing), concussions may be caused by a strike from a board, a boom or even by falls (31,32). While considering watersports, concussion accounted for 4.2-5.9% of surfing-related injuries (33). Another study found that concussion accounted for 8.2% of surfing injuries (9). Moreover, 5.9% of kitesurfing related injuries and between 3.9-13% of personal watercraft riding related injuries were concussions (33). It is important to note that this study, as with many other studies that report on injuries in extreme sports athletes, used the term "head injury" to include concussion, TBI, lacerations, skull and facial fractures, contusions etc. As there are vast differences in these injuries and how they are treated clinically, it is important from an epidemiological standpoint to distinguish between these types in further research. This remarks the current lack of data that reports on the incidence of concussions alone in many of these extreme sports. The majority of papers in extreme sports are focused around winter-based activities, like snowboarding or skiing (9); motorized vehicle sports, like All-Terrain Vehicle (ATV) competitions and motocross (23–25,34); and skateboarding (9,27). One paper observing concussions in hang-gliding reported that concussions accounted for 18.7% of hang-gliding accidents (35). As for another extreme air sport, BASE jumping, the only paper identified mentioned concussion as a "common injury", along with ankle sprains and fractures and bruised knees (26). Precise data for most other extreme sports are still missing, which may be due to their relatively new classification as extreme or action sports.

Initial diagnosis and symptoms of concussion

Appropriate identification and management of concussion from the initial onset are critical for optimal care and reduction of persistent post-concussive symptoms (9). Given the high rate of concussion in several extreme sports, a plan to have on-site concussion evaluation should be implemented when developing event-side medical coverage (36). As previously discussed, diagnosing a concussion can be challenging and is often controversial, due to the lack of precise biomarkers (e.g. no blood test or imaging study) to confirm the diagnosis. As such, inclusion of concussion trained medical providers on-site during extreme sport competitions is warranted. As initial presentation varies significantly among athletes, recognition of the many signs and symptoms of a concussion should be performed by trained medical personnel to determine if the injury involves loss of consciousness (LOC) or altered mental status (37).

According to the American Academy of Pediatrics only 10% of patients with concussions experience a loss of consciousness (24). Despite this, a study performed by Daniels et al. observed that 95% of patients who suffered a concussion after a motocross accident had a positive LOC (24). Another study found that there was a high rate (27.1%) of LOC at the scene for head injuries among skaters (27). This study also found that LOC at the scene accounted for 14.6% of airborne and 16.7% of climbing head injuries; however, it was not explicitly stated that these LOC incidents were the result of a concussion or more severe TBI (27). This may suggest an abnormally high rate of LOC concurrent with concussion relative to other published values among traditional sport athletes (e.g. football); for reference, one study found that 9% of all football concussions resulted in a loss of consciousness (38). The percentage of concussions presenting with LOC may be higher in extreme sports, because of the higher magnitude of forces and accelerations that the head may be exposed to relative to other sports, although no studies have directly investigated this idea. Although conceivable that the high speeds and forceful impacts of extreme sports lead to higher incidence of LOC, it is also plausible that an injury resulting from a LOC causes more concern leading to a higher incidence of emergency department (ED) visits. In contrast, a seemingly more apparently minor injury (one that does not involve LOC) may not result in a visit to a healthcare provider, particularly if there is no medical oversight present at the competition.

In general, the most common presentation of a concussion is headache with secondary dizziness (39). Initial dizziness at presentation is associated with 6.4 times higher risk relative to any other initial symptom in predicting a protracted recovery (40); although, many different elements may contribute to development of persistent post-concussion symptoms. Initial symptoms can also include amnesia (retrograde and posttraumatic), nausea, fatigue, fogginess, blurry vision, phonophobia, photophobia, difficulty concentrating, and increased emotionality (5,6). Concussion symptoms have been subdivided into groups including headache/migraine, vestibular, ocular, cognitive, mood/anxiety and cervical (37). Returning to extreme sports without complete recovery, shown by the absence of post-concussion symptoms, could place the athlete at more significant risk for another concussion. Due to the increased height, forces and speed of many of these extreme sports, lack of precise concentration, increased anxiety, balance/coordination impairment, inability to make last minute decisions and/or slowed reaction time could result in severe consequences as compared to more traditional sports.

Perhaps as a result of the difficulty deciphering the diagnosis among the possible presentable symptoms, many professional, collegiate, and high school organizations use time-sensitive concussion procedures for use on the sidelines or in clinical evaluations during or shortly after traditional sport practices or competition. One such program used for concussion evaluation is the Sideline Concussion Assessment Tool – 5th Edition (SCAT5), a standardized tool for evaluating concussions designed for use by physicians and licensed healthcare professionals, which incorporates immediate on-field assessments, off-field assessment, cognitive and neurological screening. Although not required, the SCAT5 can also incorporate valuable, pre-season baseline testing for athletes in the traditional sport settings to compare symptom scores and track overall improvement as they progress through the standard return to play (RTP) protocol (41). The initial assessment for concussions, which includes athlete and injury history in conjunction with symptom questionnaires and functional tests, are critical in determining concussions from other types of head injuries. Unlike most traditional sports, many extreme sports lack formal baseline evaluation procedures such as the SCAT5. In this event, comparing post-injury performance to established normative values may be useful given that this approach has similar sensitive and specificity compared to baseline evaluation (42,43). Extreme sports athletes may possess different characteristics than traditional sport athletes, yet, caution should still be used when interpreting post-injury performance among this cohort of individuals.

A formal concussion diagnosis would ideally be made by a healthcare provider, who is familiar with the athlete and an expert in the recognition and evaluation of concussions. Graded symptom checklists provide a more objective tool for assessing initial and prolonged symptoms (39). Standardized and updated sideline assessment tools (e.g. SCAT5) provide a helpful guide for the evaluation of head injuries, but contrary to organized sports, most practice sessions and participation in extreme sports are void of any sideline healthcare provider, leading to inconsistency in the assessment of head injuries. In most cases, participants are required to self-report their injuries and symptoms to their primary care provider, local urgent care or emergency department or to a sports medicine physician. Symptoms are also often underreported commonly through these channels for extreme sport athletes, creating an additional challenge for the healthcare provider. However, this phenomenon is not solely found in extreme sport athletes, but can be found also in traditional sports, where athletes may underreport their injuries due to pressure to perform from coaches, teammates or parents (7).

In a concussion, imaging is reserved for athletes where intracerebral bleeding is suspected, as conventional brain imaging methods lack the sensitivity to detect the subtle changes that may be part of the pathophysiology of concussion (44). However, among children admitted to a trauma center in Pennsylvania with a diagnosis of mTBI or concussion, a CT scan proved more likely to find abnormalities in those trauma related to high speed sport activities (27%; n=14), such as snowboarding, skiing, skateboarding and motocross riding, than to court sport activities (10%; n=2) (45). This finding suggests that physicians who treat extreme sports athletes who have sustained a likely concussion should always consider the possibility of more severe injuries resulting from high energy trauma and CT imaging should be used to rule out hemorrhage or even traumatic carotid dissection potentially resulting in brain ischemia (46).

Persistent post-concussion symptoms & management

Numerous patients, in both traditional and extreme sports, do not receive the diagnosis soon after onset, resulting in poor management that may be improper, potentially leading to negative outcomes such as altered quality of life (46). As a result, without early care and proper treatment, these athletes may be at an increased risk of persistent post-concussion symptoms (PPCS). However, currently we are unaware of any studies to this point that have directly addressed this question among this population (47). PPCS is defined as the presence of concussion-related symptoms that began at the time of injury and do not recover within one month of injury. When considering athletes, it is essential to support the psychological piece that sports play in their identity construct and the external pressure they may feel related to performance, while supporting them in the return to sport process (7). The associated symptoms that may persist during PPCS include depression, chronic fatigue, visually induced dizziness, headache, fatigue, sleep disturbance, vertigo, irritability, anxiety, apathy and cognitive slowness, or difficulties in exercising (7). The biggest clinical challenge is to determine whether prolonged symptoms are a true reflection of PPCS or a secondary manifestation of premorbid clinical depression or migraine, which are commonly concurrent conditions.

Treatment

Concussion management of extreme sports athletes should align with the most up-to-date treatment of concussed athletes in traditional sports regarding initial management of symptoms, optimizing nutrition, hydration and sleep, managing return to learn/work accommodations, early implementation of controlled aerobic activity, and rehabilitation of vestibular, ocular and cervical injury. Currently, athletes affected by concussion are encouraged to follow the most recent RTP guidelines that were designed for the use in traditional sports as directed by their physician (4). Specific RTP protocols for various extreme sports should be developed to aid the athlete in the process of gradual return to sport. As an example, for mountain bike athletes, Step 1 may include 20 minutes of light to moderate spinning on a stationary bike/trainer, Step 2 may include 45 minutes of moderate to hard cycling on a flat surface on bike trails or road riding, Step 3 may increase to a 1-1.5-hour team practice of moderate mountain bike riding on trails, Step 4 may progress to a full 2-hour team practice on trails without restrictions and Step 5 return to full mountain bike competitions. Patients with PPCS may need a multidisciplinary rehabilitation protocol. Rehabilitation should include a variety of aspects, from vestibular and cervical spinal, to cognitive and autonomic (exercising – aerobically training) (3).

In addition to the standard RTP protocol for traditional athletes, there is also ongoing research on the potential benefits of sensorimotor and neuromuscular training for injury prevention in patients reporting post-concussive symptoms. Concussions commonly cause functional disturbances of sensorimotor control that are crucial for athletes as they process a variety of visual and proprioceptive cues during sport participation. In a recent pilot study performed on collegiate soccer players, significant improvements were noted in “static balance, cervical flexor neuromotor control/endurance, and near-point convergence”, as well as a decrease in athlete injury exposure after the implementation of eight sensorimotor training programs (48). Additionally, there is evidence that similar cervicovestibular rehabilitation, as well as treatment of concurrent whiplash associated disorder, may be essential in treating those categorized with protracted symptoms in both extreme sport and traditional sport athletes (10,49). Although these studies show the promise of such programs to act as both preventative measures and rehabilitation programs, more research is needed to solidify their utility in both traditional sport and extreme sport athletes.

Prevention

As in traditional sports like hockey, football, and men’s lacrosse, the use of helmets in extreme sports has been encouraged and utilized as an injury prevention tool. Sulheim et al. (46), found that among alpine skiers and snowboarders, helmet use reduced the chance of head injuries by 60%; however, it was not specified whether these head injuries were skull fractures, severe TBIs, or concussions (24). A similar meta-analysis on concussion reduction strategies in sport found that there is a protective effect of helmets in skiing and snowboarding for head injuries, but also lacked definition of whether or not these head injuries were concussions (50). In a motocross study, 71.7% of the reported head-injury cases had confirmed helmet use (24). Although the use of helmets and protective gear may be insufficient to avoid a concussion in all extreme sports, it may reduce the severity of a head injury, which remains of great importance (51).

The use of protective headgear varies among extreme sports athletes, depending on the sport in which they participate. Headgear is rarely worn by certain extreme sports participants (e.g. surfing, skateboarding) due to the perception that it is unnecessary, may distract from the completion of certain skills required by the sport, and lack of evidence of its benefit (52). Contrastingly, helmet use is common among snowboarders, skiers and motocross athletes. Furthermore, some extreme sports, like motocross and kiteboarding, have helmet requirements depending on what geographical region the sport participation occurs (25). For example, the International Kiteboarding Association (IKA) implemented the mandatory use of helmets of at least 300 square centimeters in 2019 (53). Moreover, in a retrospective study reported by Daniels et al., all patients who presented to the emergency department with an injury received while riding at a formal motocross course were helmeted (24). This shows the willingness of extreme sports athletes, at least in motocross, to abide by regulatory rules, if implemented.

In addition to preventative equipment, environmental variables are a factor related to injury risk reduction that relate to the extreme sports athlete more than other sports (e.g. basketball). For instance, in alpine skiing and snowboarding, the risk of concussion is 2.5 times higher on rough or ungroomed snow than in soft snow (54). Moreover, concussions and head/face injuries are more common on terrain parks with the specialized jumps and ramps than other slopes (55–57). This may signify a future direction in concussion prevention measures in extreme sports that may be based on creating standardized environmental conditions for participation. Similarly, in surfing, a correlation between increased surfing competence and the incidence of head lacerations and skull fractures has been reported- most likely due to the fact that an expert surfer prefers more difficult conditions over shallow reefs while a beginner will generally surf smaller breaks (58). Further research is needed to explore this association before protective measures can be made in competition for varying age-ranges and skill level.

Contrastingly, the National Center for Injury Prevention and Control reports that children may be at a greater risk in these extreme conditions for injury occurrence because of immature or underdeveloped coordination, skills and perception and because of reduced emotional maturity and judgment compared to adults, especially in the presence of peers (18). Sharma et al. also found that teens and young adults accounted for the highest percentage of extreme sports injuries in their 12 year review of National Electronic Injury Surveillance System data for seven popular extreme sports featured at the Winter and Summer X Games for head and neck injuries (9). It is valuable for all health care providers to be aware of these risks so they can adequately educate families and coaches of risk among extreme sports athletes of varying ages and skill levels.

Additionally, a study done at a motocross race event showed approximately half of racers reported suffering concussion-related symptoms from the earlier season, while a third reported multiple concussive incidents, but continued to participate in the event (23). This continued participation immediately after a concussive event is alarming due to the elevated prospect of developing persistent post-concussive symptoms or second impact syndrome if another head impact occurs soon after the primary impact. In the same study, authors observed considerable misconceptions and lack of symptom knowledge in amateur extreme sport athletes compared to their traditional sport peers that often undergo mandatory education through centralized school-based administration (23). As a result, the benefits of formal education of athletes and their families as a preventative measure for concussions should be explored.

CONCLUSIONS

With this brief review, we aimed to emphasize the need to document and record mild traumatic brain injuries in extreme sports as well as to need to develop a RTP guideline for healthcare professionals dealing with extreme sports athletes. Furthermore, medical coverage with personnel trained in concussion management remains a key element during extreme sports competitions to ensure early injury recognition and proper management and referral. Secondly, we have highlighted the importance of prevention and multidisciplinary management. Athletes may be developing a variety of symptoms and only a dynamic therapeutic approach, which will consider the different component of concussion, will be able to ease their symptoms and reconstitute normal brain function. In the future, advanced neuroimaging techniques such as functional magnetic resonance imaging (fMRI), may help to better understand the pathophysiology of concussion and the effects of interventions in concussed athletes on a clinical basis.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (59).

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REVIEW

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Surgical treatment of muscle injury. A review of current literature and indications

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SUMMARY

Introduction. Muscles lesions are common sport-related injuries. They are usually treated conservatively with good outcomes. However, large structural muscle injuries (type 4 according to I.S.Mu.L.T. classification) are a challenge for physicians. Often, patients may suffer from discomfort and residual pain, functional impairment, and the rate of complications and re-injury rate is high. Furthermore, the lack of clear indications does not help physicians in the decision process.
Methods. We performed a systematic review of four databases (PubMed, Google scholar, EMBASE, Cochrane Library) using the Preferred Reporting Items for Systematic reviews and Metanalysis (PRISMA) guidelines. Level I (RCT), II, III and level IV studies (case series) were included. We also searched for biomechanical and animal studies.
Results. Surgical repair of type IV muscle injuries seems to provide better outcomes and higher rate to return to sport than conservative treatment, although surgical repair is not supported by level I or II studies. The suture of the muscle fibers together with the epimysium increases the mechanical resistance of the suture and reduces the risk of pull-out. This technique allows earlier mobilization, promotes healing and reduces scar formation.
Conclusions. In this article, we try to explain the rational to suture a closed muscle tear, summarize the proper surgical indications, and show the proper suture technique.

KEY WORDS

Muscle injury, rehabilitation, return to play, surgical treatment, skeletal muscle suture.

INTRODUCTION

Muscle injuries are common, and they are usually managed conservatively with good results. However, complete or sub-total structural muscle injuries (type 4 according to I.S.Mu.L.T. classification - **table I**) are a challenge for clinicians and athletes because of the high complications and re-injury rate, residual pain, and possible functional impairment (1). Furthermore, the lack of clear indications does not help physicians in the decision process. The main concern is the poor capacity of muscle tissue to regenerate itself. Moreover, there are technical difficulties in performing an effective suture. Finally, there is not yet an evidence-based rehabilitation protocol for these lesions (2). In such difficult cases, primary surgical suture has been suggested by some authors. We reviewed the current literature, and we to tried to answer five questions: 1) why a massive muscle injury should be treated surgically, 2) which are the indications, 3) which is the most effective surgical technique, 4) which are the outcomes after the surgical repair of a massive muscle injury, and 5) what are the most common postoperative complications.

Table I. This is a schematic representation of the I.S.Mu.L.T. classification of muscle injuries (1).

Direct injury		
		Contusion
		Laceration
Indirect injury	**Non-structural injuries**	**1A:** fatigue injury
		1B: DOMS (Delayed Onset of Muscle soreness)
		2: injury related to neuromuscular disorder
	Structural injuries	**3A:** minor partial injury, involving one or more primary fascicles within a secondary bundle
		3B: partial injury involving at least one secondary bundle, but less than 50% of the cross section of the muscle belly
		4: subtotal or total tear, involving more than the 50% of the cross section or the entire muscle fibres, at the MTJ or muscle belly.

MATERIAL AND METHODS

We systematically searched in four databases (PubMed, Google scholar, EMBASE, Cochrane Library) using the Preferred Reporting Items for Systematic reviews and Metanalysis (PRISMA) guidelines. We used the key words "muscle belly, muscle injury, muscle laceration, repair and muscle suture". The article research was extended from 1978 to December 2019/January 2020. Level I (RCT), II, III and level IV studies (case series) have been included. We also search for biomechanical and animal studies. Scientific papers excluded are narrative review, systematic review, case report or technical notes. The study has been performed according the international and ethical standards of the journal (3).

RESULTS

The search provided a total of 75 articles. Thirty-one studies were included in this review. The others have been excluded because they did not meet the inclusion criteria. In particular, several papers were excluded because they focused only on tendon injury or described a surgical technique with no outcome data.

Why should we suture a muscle injury?

Massive type 4 muscle tears are rare in ordinary orthopaedic practice, but they can produce marked negative consequences and disability for patients, even in the long-term. Although a torn muscle can heal, this process leads to replacement with sclero-fibrous tissue which has poor elastic, mechanical properties, and contractile capability. Moreover, massive muscle tears heal slowly and often incompletely, leaving a mass of scarred and immature tissue. This results in a reduction of contractile force and elastic properties of the muscular belly, alteration of strength transmission and may predispose the patient to further injury. Animals studies showed that immobilization to allow healing can lead to the development of scar tissue (4,5). On the contrary, early mobilization promotes healing and proper orientation of muscle fibers in a more orderly manner, as well as reducing the formation of scar tissue and the loss of elasticity (5). Early mobilization, moreover, reduces muscle atrophy, improving overall functional recovery after injury. Naturally, early mobilization after surgery require the muscle repair to be reliable.

Which are the indications for muscle surgical repair?

In the case of a large muscle laceration, urgent surgical repair is intuitive and mandatory (**figure 1**). In the case of a closed, indirect muscle injury, the choice is much more difficult. Currently, there is no scientific evidence about surgical treatment of muscle tears, and the indication is discussed case by case, according to the kind of patient and functional demands.

According to the available literature, all patients who underwent surgical repair of an acute muscle injury (within 4 weeks), sustained a complete or sub-total injury of the muscular belly or at the myotendinous junction (type 4 according I.S.Mu.L.T.) (6,7,8). The indications for surgical repair of a chronic injury were pain and/or limitation during sporting or daily life activities subjective or objective loss of strength compared to contralateral side, fatigue, chronic pain even at rest (9,10,11), There are no articles published about hematomas evacuation and muscle suture after a direct trauma (**table II**).

The operative timing is extremely variable. In all the examined studies, acute injuries are those which were treated within 4 weeks of the initial trauma, while chronic injuries have been treated from 4 weeks to more than 1 year later. Better functional results and recovery were reported in patients operated within 4 weeks. However, there is still no clear evidence on the ideal timing for surgery (8,10).

Table II. Indications for surgical repair of muscle injuries.

Acute Muscle tear (< 4 weeks)	Chronic muscle tear (> 4 weeks)
Type 4 muscle injury	Young age
Young age	Pain during sport activity
High level sport, intensity and frequency	Limitations in sport activity
Persistence of pain after 1-2 weeks following intense physiotherapy	Fatigue
Open Wound	Loss of strength compared with contralateral side
	Pain and limitations during activities daily life
	Pain at rest

Moreover, there is no agreement in literature about the age of patients. Usually patients are young, between 18 and 43 years, but there is not a real limit of age beyond which the intervention is not indicated. Finally, we don't know if the gender of the patients could affect the final outcome.

Which is the most effective surgical technique?

The suture of a muscular belly is technically demanding because muscular tissue has unique characteristics. First, the suture is more difficult because of the low resistance of the muscle tissue, which determines a high rate of failures and stitches pull-outs. Indeed, biomechanical studies on animals show that muscle fibers are the weakest part of the suture (12). The muscle fibers are parallel to the vector through which force is applied, and this makes the suture more subject to failure (13).

Figure 1. Complete cutting wound of the rectus femoris, vastus intermedius, and partial tear of the vastus lateralis following a ski downfall.

As previously mentioned, early mobilization promotes wound healing, but early mobilization needs a strong suture to withstand the forces applied. A secure muscle repair is not easily achievable, and studies on surgical techniques are extremely limited. Muscle suturing techniques can be schematically divided into simple and complex. To the first group belong the figure-of-eight suture and the horizontal mattress sutures, while to the second ones the modified Kessler and Masson-Allen techniques. When the repair also includes the suture of the epimysium or perimysium, the technique is called combined. Currently there is no evidence of which is the best technique.

Seven biomechanical studies were selected in order to understand which is the most effective surgical technique for muscle injury. Skeletal muscle is organized by its connective tissue components with epimysium surrounding the muscle as a connective tissue sheath, perimysium surrounding bundles of myofascicles, and endomysium surrounding myocytes. These studies showed that including the epimysium improved the tensile strength and reduced the pull-out of the sutures. In 2005, Krag et al. (14) demonstrated that the incorporation of the epimysium into muscle repair significantly improved the biomechanical properties of sutured muscle bellies when compared with repairs with perimysium. The epimysium is a thick fibrous sheath made of two layers, and the incorporation of the epimysium was biomechanically superior to muscle repair without epimysium (mean maximum load of 30.4 N compared to 19.2 N) (14). In the same year, the same group published an animal study comparing the tensile strength between the Kessler and combined techniques (modified Mason-Allen for the fibers plus the peripheral suture for the epimysium) (13).

The latter technique showed a tensile strength two time higher the Kessler. More recently, He at al. (15) compared three different types of sutures: simple mattress suture, Kessler-type suture, and Mason-Allen combined suture. The Kessler and Mason-Allen techniques showed similar tensile strength (15.5 N and 13.2 N), and both were superior to simple stitches (4.4 N). Crow et al.16 proposed the use of a collagen scaffold (SIS - Small Intestinal Submucosa). According to the authors, this biological scaffold would favor wound remodeling, thus improving the healing and increasing the mechanical resistance of the suture. Recently, Goyal et al.17 compared a self-locking thread suture (V-LOC®, barbed suture) with a normal non-resorbable suture (Ethibond®), and they found that barbed suture increased the load to failure and decreased the displacement of the repair site compared to normal suture. Repair of neglected injury is more difficult due to the scar tissue, muscle stumps retraction and the loss of elasticity. Therefore, some authors proposed an augmentation technique with LARS ligament® (Ligament Augmentation and Reconstruction System) in one case of a neglected tear of the rectus femoris muscle in a 17-years-old male football player (18). They reported that the use of LARS ligament®, as reinforcement of the muscular suture, allowed immediate full passive mobilization of the knee, early graduated physiotherapy programme, and that the patient was able to return to running and his previous level of sport without any restrictions. However, no other studies on the augmentation device have been published in literature.

What are the outcomes after the surgical repair of a massive muscle injury?

The evidence of surgical treatment of type 4 muscle injuries is low, because few case series and case reports are reported in literature. Furthermore, there are no level I studies comparing surgical treatment with conservative management. Therefore, results were analysed according the available studies and the involved muscle (**table III**).

Biceps brachii muscle

In 2002 Krag et al. (6) published a retrospective case control study on patients who suffered closed transection of the biceps brachii belly. Nine patients treated surgically have been compared with 3 patients treated conservatively. All patients were paratroopers who suffered the same injury during a parachute jump. The average age was 21 years old, range 18-26. All patient fully recovered the function of their arm at final follow-up, but the authors found significant improvements in terms of function and satisfaction in patients who received surgical repair compared to those treated non-surgically. The cosmetics was also better in patient treated surgically. No complications were reported in either group. In conclusion, the authors recommended the surgical repair for patients who present a tear greater than 95 % of muscle diameters. Two other studies have been also published, for a total of 23 patients. (6,18). The authors agreed that surgical treatment is recommended when the tear is greater than 50 % of the biceps brachii belly (type 4 according to I.S.Mu.L.T. classification)

Table III. Clinical studies regarding the suture of muscle injury.

Author	Year	Study type	Injured muscle	Level of evidence	N. cases
Heckman et al.[19]	1978	Case series	Biceps Brachii	IV	9
Botte et al.[7]	1987	Case series	Biceps Brachii	IV	14
Kragh JF Jr et al.[6]	2002	Case series	Biceps Brachii	III	12
Miller.[36]	1977	Care report	Gastrocnemius muscle	IV	1
Cheng et al.[35]	2012	Case series	Gastrocnemius muscle	IV	2
Orava et al.[39]	2015	Case series	Hamstrings ossificants hamstring	IV	11
Orava et al. [49]	2017	Case series	Hamstrings Myositis ossificants	IV	32
Straw et al.[20]	2003	Care report	Rectus femoris	IV	1
Taylor et al.[9]	2012	Care report	Rectus femoris	IV	1
Lempainen et al.[8]	2018	Case series	Rectus femoris	IV	27
Lempainen et al.[34]	2006	Case series	Proximal origin of the hamstring muscles	IV	24
Julien et al.[38]	2011	Tech. Note	Muscle laceration – direct trauma	IV	6
Oliva et al.[37]	2013	Case report	Muscle laceration – direct trauma	IV	1

Rectus Femoris muscle

In 2018 Lempainen et al. (8) published a study on 27 elite football players treated surgically for rectus femoris grade III muscle injury (type 4 according I.S.Mu.L.T). Patients who suffered for injury of the direct or reflex head were excluded. The indications for surgical treatment complete tear of the muscle belly, that was confirmed at the MRI, pain, objective and subjective strength loss, functional limitations, re-injury, and chronic pain on injured area. The timing of surgery was different, 8 patients were treated within 4 weeks from injury (acute injuris), while 19 cases from 1 months to 1 year (neglected injuries). Good to excellent results have been reported in 74% of athletes, and most of patients (20 patients) returned to practice sports at the same preoperatory level, without pain limitation, or with a little pain that did not interfere with sporting activities. Patients returned to compete 5 months after surgery on average. Only in one case of chronic injury, the patient referred pain and limitations also in activities daily life, and a second surgery was performed.

Two case reports on young players (aged 17 and 22 years old) suffering from chronic muscle injury of rectus femoris have been reported (18,19). Both patients referred pain and functional impairment, even after a complete and specific rehabilitation program. At the clinical examination, the patients had hypotrophy of the quadriceps, a loss of strength about 60 % compared with contralateral side, fatigue, and they were not able to return to sport. In the first case the injury occurred at the muscle belly, just below the muscle-tendon junction, while in the second case the rupture involved the proximal muscle-tendon junction. Both players return to play football at the same preoperatory level, and they were satisfied with the surgery.

Hamstring muscle

Although hamstring muscle injuries are common, especially in athletes, there are currently no clear indications about their surgical treatment (**figure 2**). The lack of scientific evidence may be also the result of a confusing terminology in the literature.

Firstly, the injured area should be defined as proximal, middle third, distal (1). Only injuries of the proximal third and insertion have been widely described in literature, therefore, when we usually read about hamstrings ruptures, authors often refer to proximal injuries only (20,21).

In addition, there is a confusing terminology in the classification system of these injuries. In a recent review of literature, hamstring tears have been classified in grade I, II and III (22). Grade I injuries were defined as minor tears, without rupture of the musculotendinous junction (MTJ), with little edema, mild pain, and no or minimal functional impairment. Grade II injuries were considered major injuries, with partial rupture of the MTJ, or an isolated complete rupture of one component of the muscular complex. For example, an isolated complete rupture of the semimembranosus or biceps femoris, was considered a grade II injury because the rest of the complex was intact. A grade III injury was a complete rupture of the muscular complex, which often coincides with the avulsion of tendons from their proximal insertion on the ischial tuberosity (23). Indications for surgical treatment of proximal hamstring injuries are not clear, nor supported by level I or II studies. This may depend on several reasons: the complexity of the anatomical region, the lack of a universally accepted classification, different functional demands of the patients, and the expertise of the surgeon. Despite this lack of evidence, more and more surgical repairs have been recently carried out in case of complete rupture of the proximal third with a stump retraction greater than 2 cm, or partial rupture with disruption of the proximal insertion in patients who already underwent reconstruction of the anterior ipsilateral cruciate ligament with gracile and semitendinosus tendons (23). Chronic pain and functional impairment despite specific physiotherapy should be considered as other indications to surgical repair, as well as patient's age and functional demands.

Surgical timing is important since acute lesions operated within 4 weeks have reported better results than chronic ones (4-6 months). Actually, some authors suggest surgery

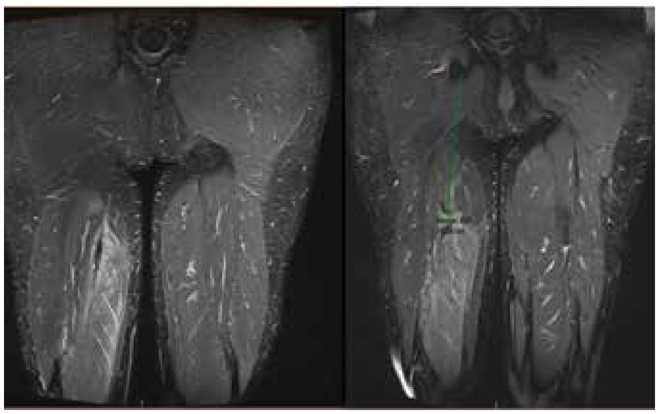

Figure 2. This picture shows a muscle injury type 4 of the semimembranosus muscle of a 47 years old patient. The injury occurred during practice martial arts. Muscle tear on semimembranosus occurred 16 cm lower than ischiatic tuberosity, and muscle insertion appears continuous. The patient was treated conservatively. A relapse occurred 3 months after injury, during the rehabilitation program. After 1 year, the patient returned to practice martial arts, but he referred occasionally light pain.

within 2 weeks (23). A systematic review on 18 studies and more than 300 cases of proximal hamstring injury confirmed this data: surgical treatment achieved better results in terms of pain, functional recovery and return to sports than conservative treatment, and patients who underwent surgical repair within 4 weeks from injury showed better outcomes and lower recurrence rates than patients treated after 4 weeks (24) However, this review takes into account only complete proximal hamstrings injuries (avulsions), while there are no data on the partial ones.

The problem gets even more complicated when dealing with MTJ injuries, the so-called partial injuries, for which the literature is extremely poor. Lampainen et al. (25) published a paper in 2006 on 48 athletes who underwent surgical treatment for a partial lesion with tendon involvement of the hamstring, reporting good to excellent results with resumption of the previous sporting activities in 88% of cases. Recently, an increasing number of authors is surgically treating partial lesions of the myotendinous junction in high level athletes (23). However, there is no scientific evidence yet.

Adductor muscles

Sports-related groin injuries are common among athletes. Of injuries within this region, 64% involved the adductor muscle complex. The mechanism of injury typically involves a noncontact, eccentric load with forced abduction and extension of the hip, resulting in disabling groin pain (26). Adductor muscles injuries account for about 20% of all muscle injuries in athletes. Most adductor ruptures occur at the proximal or distal MTJ, while less frequently proximal or distal adductor tendons avulsion occur. These injuries are predominantly seen in the athletic male population, and the most commonly injured adductor muscle is the adductor longus muscle. Injuries at the MTJ are traditionally treated conservatively with satisfactory outcome, but there are no reports in literature about the surgical repair of adductor muscles injuries.

Management of proximal adductor avulsion injuries is controversial. Nonoperative management for an acute avulsion generally provide good results (27). However, this treatment may result in continued groin pain and decreased function. So, some authors actually suggest that surgical fixation, and surgical reattachment with boney anchors seems to provide better outcomes, shorter return to sports, and significant improvement in outcome scores compared to non-operative treatment (28,29,30,31) However, few case series and case reports are published in literature. Finally, adductor tenotomy has been advocated for chronic groin injuries in some cases (32).

Gastrocnemius muscle

Cheng et al. (33) published 2 cases treated surgically for a large close injury of the belly of the medial gastrocnemius muscle. The first was a 37 years old patient, treated within 10 days from injury, while the second patients, a 43 years old woman, was treated surgically 7 months post-injury. In both cases MRI showed a complete rupture of medial gastrocnemius belly at the muscle-tendon junction, and a retraction of the muscle fibers. Both patients return to sport at 2- and 10-months post-surgery (respectively). The patient with the neglected injury referred light pain, which does not limit her activity. For this reason, the authors suggested to perform the surgery during the acute phase. Millers also reported good results in a patient affected by a neglected tear of the medial gastrocnemius muscle, who was not able to walk on tiptoes before surgery (34).

Laceration injury and open wound

Disinfection and surgical treatment of a muscle laceration caused by direct trauma with sharp objects (e.g. cutting wound) is mandatory. Surgical treatment should be performed immediately (**figure 3**). Optimal results are reported after the suture of wide muscle laceration (**figure 4**) (35,36). However, few case reports are available in literature.

Intramuscular calcification

Currently, there are no evidence-based recommendations about the exeresis of post-traumatic muscle calcifications, since few level IV studies and case reports have been published (37,38,39). Intramuscular calcifications (myositis ossificans) usually arise from large injuries with extensive intramuscular hematoma, but their pathogenesis is not clearly understood yet. However, the onset of calcifications delays the healing process and may result in a significant functional impairment, especially for the large ones. Calcifications typically occur in young male athletes, and commonly affect the quadriceps, the hamstrings, and biceps brachii (40). The incidence is not clear yet, and it ranges from 0.5% to 9% after a direct injury, according to authors (41,42).

The diagnosis of myositis ossificans should be considered if pain and swelling persist after 10-15 days post proper conservative management, or if symptoms worsen after 2-3 weeks from the trauma (43). The patients commonly report swelling and stiffness. A reduction of the ROM is usually observed at the clinical examination. MRI is useful since the early stages, while X-rays become positive after about 2-3 weeks and evident after about 2 months.

Figure 3. Laceration wound caused by a ski injury. Total vastus lateralis muscle tear in 19 years old guy.

The treatment of the myositis ossificans is conservative first. A few studies showed that the majority of the patients treated with specific rehabilitation protocol return to sport at the same level before the injury, even if the rehabilitation process is longer than an isolated muscle injury (44,45). When calcifications, instead, cause pain and functional impairment, the majority of authors agree on their surgical removal. Surgical exeresis of a calcification should be performed 12 to 24 months after the end of the pathogenetic process. Commonly, an open procedure is performed, although some authors described the arthroscopic exeresis in case of calcifications at the rectus femoris insertion (46). Recently, Orava et al. (47) reported good to excellent results in more than 80% high-level athletes who underwent the exeresis of calcifications at the proximal third of their hamstrings. In these cases, the surgical exploration and neurolysis of the sciatic nerve is essential because it be trapped by scar tissue and be a source of pain.

What are the most common postoperative complications?

The most frequent complication, besides the failure of the suture itself, is the post-surgical hematoma. However, there are no information about the incidence, nor whether the use of low molecular weight heparin (LMWH) may promote this complication. There is no indication about the use of postoperative drainage or a compression bandage to reduce the incidence of the complication. Post-surgical hematoma is a despicable complication because it delays the rehabilitation of the patient and may promote the formation of scar tissue and intramuscular calcifications. Surgical evacuation may be indicated for the largest ones (8).

CONCLUSIONS

Muscle injuries are frequent, and often occur during sporting activities. Type 2 and 3 injuries are treated conservatively with excellent results, while conservative treatment of type 4 injuries does not always produce the desired outcomes, particularly in high level athletes. Surgical suture of type 4 muscle injuries seems to provide good outcomes with a high rate of return to sports activities, reducing the complications and recurrence's rate. Suture of the muscular fibers together with the epimysium improves the suture stability, allowing an earlier and safer mobilization. However, there are no level I nor II studies supporting surgical treatment of muscle injuries. Therefore, we need studies with a higher

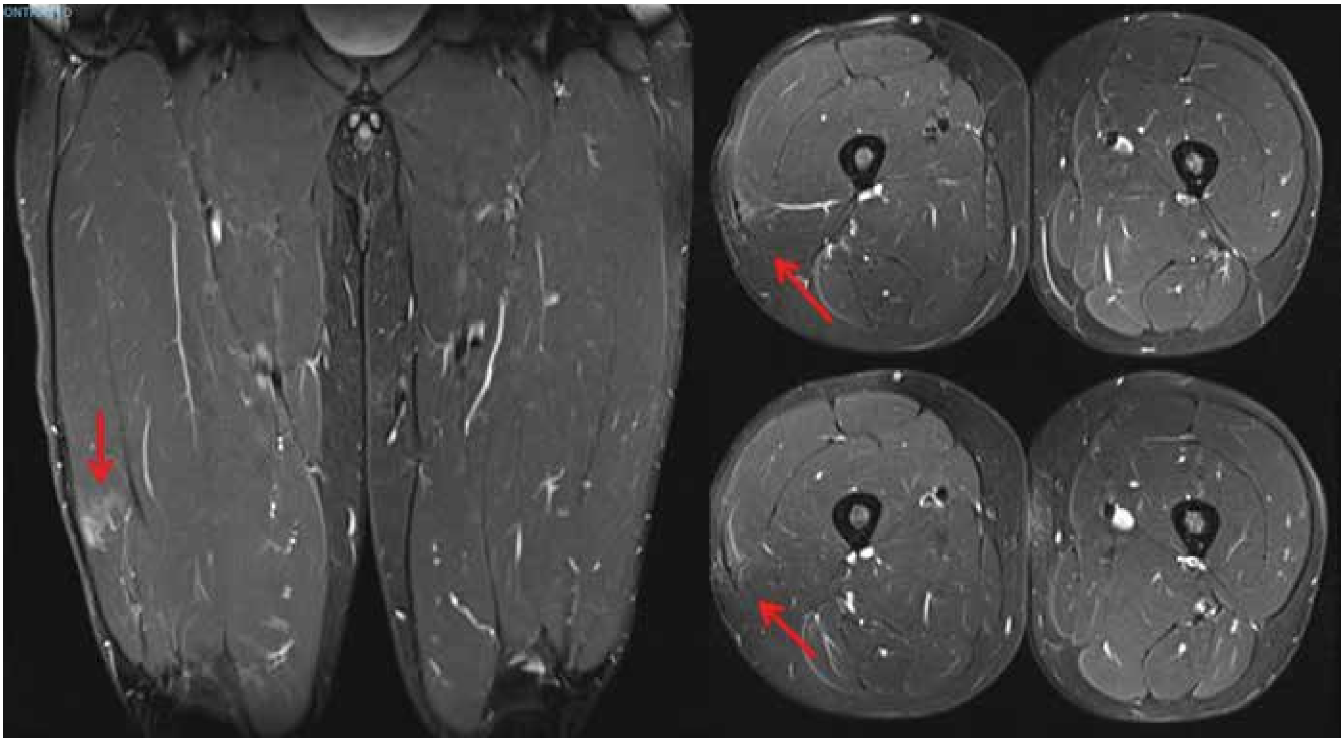

Figure 4. MRI scan 1 year post-injury. The patient returns to play volleyball at the pre-injury level pain free.

scientific evidence to improve our knowledge, in order to guarantee the best treatment to our patients.

KEY POINTS

- Early mobilization, compared to immobilization, can improve the healing process and stimulate the formation of more functional muscle tissue.
- The suture of muscle fibers together with epimysium improves the mechanical resistance and reduce suture pull-out.
- The suture of type 4 muscle injuries seems to improve the outcomes and to reduce the recurrence rate.
- There is no evidence about the timing of surgery, nor the age of the patients. Few articles showed that the outcomes of acute muscle injuries are better compared to chronic injuries.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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ORIGINAL ARTICLE

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Conceptualising Performance Enhancement in Extreme Sports: Combining Physiological and Psychological Perspectives

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SUMMARY

Background. Extreme sports, such as BASE jumping and big wave surfing, are emerging as highly popular sporting activities with profoundly different characteristics to traditional sports. To date, research has generally assumed that performance in extreme sports is based on a homogenous understanding of extreme sports and extreme sport participants.

Methods. A narrative examination of the physiological and psychological literature on extreme sports.

Results. The traditional perspective is limited and overlooks important and nuanced differences which are essential for performance enhancement. Athletes are not a homogenous group of individuals and performance environments provide different challenges. A more nuanced assessment of extreme sports reveals that effective performance and survival in extreme sports is centred on the development of the capacity to make fast, accurate decisions under severe physiological and psychological stress, where getting it wrong might result in serious injuries or death. Enhancing performance in extreme sports depends on understanding these issues and designing programs that appreciate the unique relationship between the individual athletes, the task and the performance environment. Like traditional sports, extreme sports necessitate precise attunement to information in the performance environment. Additionally, the extreme sports environment is constantly changing and dangerous.

Conclusions. A one-size-fits-all approach is not appropriate for performance enhancement in extreme sports. Extreme sports are also different to traditional sports. Gradual immersion in the activity will facilitate attunement to information in the performance environment and the realisation of capacities to make effective decisions essential for successful performance.

KEY WORDS

Physiology; psychology; extreme sports; BASE jumping; sport-specific.

INTRODUCTION

Extreme sports, such as BASE jumping, big wave surfing, rope-free climbing, free-diving and waterfall kayaking, are defined as physical activities where death is a potential outcome of a mismanaged mistake or accident (1). Despite this, participation rates across various extreme sports seem to be increasing faster than many traditional sports (2, 3, 4). For the most part, suppositions about extreme sports performance and its enhancement have been based on interpretations of research conducted in traditional sporting contexts (5, 6). However, extreme sports differ from traditional sports in many fundamental ways, which have profound implications for understanding performance and performance enhancement: 1) Extreme sports are mostly non-competitive activities resulting in winning or losing (7); 2) Poor performance in extreme sports is potentially dangerous where death of a participant is a real possibility (8); 3) While activities are still evolving and urban extreme sport examples exist, they usually take place in natural environments, rather than the tightly constrained performance environments of traditional sports, (9); 4) they are not generally governed by external regulations or rules that define how the 'game' should be played (7); 5) performance criteria are continually evolving and most often centred around creativity and aesthetics rather than traditional quantitative parameters (e.g. distance, time, score) and the appreciation of high-level performance is not restricted by these pre-set quantitative parameters (10, 11, 5). While there are similarities, any assumption that performance in extreme sports is the same as other outdoor or adventure sports is incorrect. Although both are physical activities undertaken in natural environments, mishaps in adventure sports are unlikely to lead to death, which indicates fundamental differences (1, 12). The environmental variables in extreme sports are more extensive and can be dramatic and unstable. Effective performance relies on the profound understanding of these variables and how unpredictable they can be (i.e. big waves, high mountains with unstable snowpack and weather, wind variability in flying). Individuals need to be attuned to information in these environments, have the capacity to respond to rapidly-changing unpredictable conditions (at times by withdrawing from the activity when conditions are too dangerous), and have the ability to make split-second decisions while participating to achieve their goals, or simply to survive.

For the most part extreme sport research has focused on understanding the reasons behind the choice to participate (1, 13) and using traditional theory-driven arguments, which frequently portrays the participants as thrill-seeking, reckless, self-destructive, and pathological daredevils. This perspective often attributes some deficiency to the participant and emphasizes an unhealthy desire for risk and risk-taking as the main driver for participation (1). This approach does not reflect the experience of participants and assumes that the main determinant of performance is the innate ability to handle risks (15). Recent research on extreme sports has revealed that motivations are broader, more positive and life-enhancing, and suggests that effective performance is determined by more than the innate ability to handle serious risk (8, 13, 16,17). However, knowledge about these functions is still limited. This paper outlines a conceptual framework for understanding effective performance in extreme sports.

Performance enhancement in extreme sports

Enhancing performance in extreme sports presents nuanced challenges which are less apparent in traditional sporting contexts. Performance enhancement research in traditional sports has resulted in the appreciation that each sport has distinct characteristics that demand sport-specific knowledge to facilitate performance enhancement. Additionally, research has proven that each type of sport has subtly different needs for performance enhancement across multiple areas such as decision-making, emotional management, muscle preparation, nutrition.

In contrast, extreme sports are, for the most part, still perceived to be a homogenous group of activities (1). Attempts to understand extreme sports have most often focused on differentiating extreme sports from traditional sports on the basis of perceived differences in task, environmental, individual and sociocultural factors. Extreme sports are perceived to be dangerous sports, performed in dynamic, uncertain and even dangerous physical environments, undertaken by high thrill-seekers, people with a pathological need for risk or people who belong to specific sociocultural subgroups (5). The focus on differentiating extreme sports from traditional sports has led to limited research into the performance enhancement aspects of extreme sports.

In this paper, focus is given to why sport-specific training is crucial in extreme sports where death is the most likely outcome of a mismanaged mistake or accident (1). The physiological and psychological demands of each extreme sport are heavily influenced by the activity being performed and the environment in which it takes place. During free diving, for example, considerable pressure is exerted on an athlete's body as he/she descends to depths of up to 100 m, requiring great physical resilience. Physiological requirements for extreme mountaineering (e.g. climbing Mount Everest without oxygen) are much different than those required for BASE jumping. Participation requires that the athlete has a profound knowledge of the specific performance environment and trains for participation in that specific environment. Additionally, the psychological requirements for multi-day activities, such as polar expeditions, are not the same as those required for solo, rope free climbing. As previously explained, performance in extreme sports is not limited by the traditional idea of winning and losing. Instead, the physiological and psychological requirements for effective performance in extreme sports include the capacity to survive in extreme environments as well as to prepare effectively. This paper argues performance enhancement in extreme sports is underpinned by the relationship between individual characteristics, task characteristics and environmental characteristics.

METHODS

This paper reviews historical and contemporary scientific articles aims to explore the possibility to develop specific systems and methods to enhance performance in extreme sports, combining physiological and psychological perspectives. This review is a narrative based on critical studies and does not examine any hypotheses. Indeed, due to the sparse and fragmented literature on this subject area, it was not considerate adequate to conduct a systematic review.

Psychological perspectives

Traditionally, performance enhancement in extreme sports has been examined from epidemiological and psychological perspectives. Epidemiological research has focused on analysing accidents, injuries and causes of death in extreme sports to improve performance-related issues within individual sports (5, 19, 20, 21, 22). Epidemiological research has considered task, individual and environmental factors where the emphasis has been on task and environment. Psychological examination of extreme sports participation and performance commonly concentrates on personality. The primary assumption has been that participation and performance are dependent on the need to experience and manage high risks. However, this approach has been criticised because 1) it does not reflect the lived experience (1), 2) research has identified heterogeneous personality types with limited applicability of this finding (23, 24) and3) recent research suggests that the risk-taking personality type is more likely to be aligned with the prevalence of accidents and injuries than with improved performance (15). An important ramification of the traditional dominant risk focus is that other, perhaps more important, psychological aspects have been overlooked (25). From a psychological perspective, effective performance relies on the capacity for critical decision-making in situations accompanied by potentially severe consequences for poor performance. This process involves rapid integration of objective information (rapidly changing environmental variables) and subjective experiences (focus, fear, exhaustion). The regular requirement for split second decision-making under pronounced psychological and physiological stress (for example changing a flight course due to wind variability in proximity flying) is crucial in extreme sports performance. One of the fundamental psychological skills required to perform is the ability to manage fear and stress and even flourish despite its prevalence (9). However, this does not mean that participants do not experience fear. Participants report that they experience fear directly related to the knowledge that a mismanaged mistake could mean death. This research highlights that successful participants spend considerable time and energy mastering the activity, understanding the environments where it is practised and recognize their own capabilities to respond in order to minimise the chance of accidents (including not infrequently deciding to walk away) (1). Strategies to maximise effective participation in this context includes training for mishaps (e.g. big wave surfers using rocks to keep them submerged when practising being underwater), adapting the findings of research into the causes of previous accidents into their activity, and becoming experts on the environment relevant to their activity (1). Participants must also be able to focus on and be present in the activity and attuned to information in the immediate environment (25). Siefert et al. (26) found that expert rock climbers can successfully perceive and act on relevant information in the environment. Hetland et al. (27) examined emotional expression while participating in skiing and determined that performance was linked with high-level focus, likely related to the difficulty of the activity. They also noted that performance was often accompanied by experiences of psychological and physical discomfort- a point recognised in research into polar expeditions (28). Effective performance depends on how well the athlete is psychologically prepared for and adapts to extreme environments (29).

Effective participation depends on self-awareness and the capacity to analyse the environment. In using jumping for example, if the analysis does not suggest a safe jump, then participants invariably decide to walk away (7). Negative feelings are not managed like they might be in traditional sports, rather they are integrated and used as information to guide effective decision-making. Self-knowledge and the capacity to act on self-knowledge can differentiate between life and death (30).

As evidenced by current literature, performance is influenced by capacities to a) make decisions that might include walking away if appropriate, b) live with and accept fear as important information, c) be focused or present during the activity, d) perform when physically and psychologically uncomfortable, e) profound self-awareness of personal capacities, f) commitment to psychological and physical skill development and g) profound knowledge of the environment and attunement to information in the environment (1). Extreme sports performance and performance enhancement is achieved by integrating all the above into split-second decision-making in unstable and dangerous situations.

Physiological perspective

Physical and psychological predisposition, influenced by genetic makeup, is the fundamental building block for athletic success and has been the driving principle behind talent identification programmes worldwide (30). Once identified, sport-specific training hones an athlete's skills (31). Likewise, participation in extreme sports builds upon genetic physical and mental attributes, while employing a progressive training model to maximise success.

Performing the chosen activity in physiologically demanding conditions is a hallmark of extreme sports. Whether the conditions are excessive heat, high altitude, or lack of oxygen, the environment provides the physiological challenges associated with extreme sports participation.

All humans exhibit a mammalian diving reflex upon submersion in water, that induces bradycardia and peripheral vasoconstriction, to minimise the rate of oxygen utilisation within the body and subsequently delay the urge to breathe (32). However, apnea-trained free divers have exhibited the ability to develop greater lung volumes than untrained humans (33). They also display enlarged spleens which, upon contraction, increase the amount of oxygen carrying red blood cells (34, 35) and an enhanced diving reflex, enabling greater depths to be reached or apnea times to be achieved (33). These training-induced responses facilitate an extended timeframe before physiological urges to breath (diaphragm contractions) are triggered. The current world record for breath holding by a free diver is over 24 minutes. As seen, physical and mental training provides free divers with an acute awareness of their physiological signals and the ability to extend apnea time past their innate physiological breaking point. However, this is not the only sport which athletes must train for hypoxic environments.

Whether ascending Mt. Everest (8,848m), BASE jumping (current world record of 7,700m from Mt. Cho Oyo), extreme hang or paragliding over Broad Peak (8051m), or ascending 4526 vertical metres in a single flight (37, 38), hypoxic environments challenge the physical and mental capability of many different extreme sport participants. Exposure to these extreme altitudes, without proper training, can reduce the oxygen content within the body to dangerously low levels. However, in the same way that divers can train to improve their body's resistance to apnea, controlled exposure to high altitude (greater than 1500m) can be used to induce both acute and chronic acclimation responses for preventing hypobaric hypoxia (36). The body's initial response to high elevation exposure is an increased heart rate to deliver more blood, and consequently sufficient oxygen to active tissue. Long term acclimation, including training at progressively increasing altitudes, produces favourable physiological adaptations to increase oxygen levels. Increases in the concentration of circulating red blood cells and cellular adaptations are designed to improve circulating oxygen levels and oxygen delivery to the active skeletal muscle cells (39).

While oxygen regulation is one challenge of extreme sports, extremes of ambient temperature also present challenges to normal human thermoregulatory capabilities. For example, the Marathon des Sables, a six-day event in the Sahara Desert, and Badwater 135 mile, commencing in California's Death Valley, represent two of many events which chronically stress an athlete's ability to withstand extreme heat. Aside from an immediate increase in sweating, enhanced skin blood flow and hormonal regulation to preserve body water automatically occurs in all humans when elevations in internal body temperature eventuate; athletes undertaking these extreme endurance events will also display significant levels of heat acclimation. Increased sweat output and an earlier onset to improve evaporative heat loss, as well as expansion of plasma volume help maintain total body water and regulate blood pressure; and a reduction in the internal body temperature set-point all contribute to minimising the risk of potentially fatal exertional heat illness (40, 41, 42).

CONCLUSIONS

Performance enhancement in extreme sports cannot be based on the assumption that extreme sports are a homogenous group of activities. Instead, research suggests that there are considerable nuances between each specific discipline, which is dependent upon the relationship between the individual, the activity and the environment. Research suggests that, similar to traditional sports, participants can improve their psychological and physiological requirements through sport-specific training to increase their performance. How this is done will depend on the characteristics of the environment and chosen discipline. As demonstrated, the competencies required for free diving vary greatly from in polar expeditions or BASE jumping. Such understanding is crucial to designing an effective training and preparation strategy for the intended activity. Generic training that assumes one-size fits all extreme sports is not appropriate. Rather, it must be specifically suited to each individual and discipline. Designing training systems in an extreme sport will require a focused appreciation of the relationship between specific performance related environmental and task needs, and individual characteristics. The central tenet of performance in extreme sports is the capacity to endure severe extreme physiological and psychological stress in unstable environments and make effective decisions in context. The development of these capacities suggests the development of individual capacities for psychological adaptation to physiological stress and extreme environments.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (43).

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An Ecological Dynamics Perspective of Return to Play Decision-Making for Extreme Sport Athletes

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SUMMARY

Background. Extreme sport participation occurs for many reasons. A commonality for many is the high risk of serious injury or death, particularly in association with mismanaged execution.

Methods. This review describes a conceptual return to play decision-making model for extreme sport athletes based on considerations of ecological dynamics.

Results. In guiding the extreme sport athlete through sport-specific training simulations and secondary injury prevention education, the rehabilitation clinician must develop a thorough understanding of the sport and the factors that contribute to their safe performance.

Conclusions. The interaction of multiple factors including (but not limited to) experience and skill level, personality, conditioning level, overall health and injury status and the injury risks associated with many extreme sports make return to play decision-making particularly difficult.

KEY WORDS

Return to play; adventure; sports; training; education.

INTRODUCTION

Any attempt to define extreme sports should consider emerging creativity and the trade-off between order and instability as essential elements (1). The lack of consistency with the term, extreme sport, means that those who wish to understand this field often have to develop their own criteria as a starting point (2). Both high-risk and extreme sport represent any sport that is defined as one in which the participant must accept the possibility of severe injury or death as an inherent part of the activity (3). However, some extreme sports, such as climbing, possess lower injury incidence and severity scores than traditional sports, such as sailing, basketball and soccer (4). For example, the death rate reported among climbers in the United Kingdom is significantly lower than that reported for motorcycle riding (5). Part of the difficulty in being able to define extreme sport is that they possess many other factors aside from risk that include, but are not limited to, spatial, emotional, individualistic and transgressive dimensions (6). Extreme sports are temporal emergent products of development within individual, task and environmental constraints, being open to continual evolution through creative exploratory behaviors and technical innovations (1). The most common terms considered representative of extreme sports include alternative, action, adventure, lifestyle, media-driven, and individualism (2), however, extreme sport appears to be most used and this is what we will adhere to in this concepts paper.

Common misconceptions of extreme sport athletes is that they are solely risk-taking, adrenaline and thrill-seeking or death-defying individuals. In contrast, many participants describe experiencing positive, deeply meaningful and life-enhancing events (1). Conceptualization of extreme sports participation, using more qualitatively-based phenomenological research methods, enables researchers and clinicians to better understand how extreme sport athletes experience certain phenomenon, while also helping control for biases and preconceived assumptions regarding sport-related life experiences, feelings, and responses to particular events. With this approach, the rehabilitation clinician will likewise develop a more holistic perspective as they develop strategies for treating and evaluating these athletes.

Reasons for extreme sports participation and injury risk

While many traditional sports promote teamwork, extreme sports tend to be focused on goals that challenge the individual. Cohen et al (2) operationally defined extreme sport as a predominantly competitive (by comparison to others or self-evaluation) activity within which the participant is subjected to natural or unusual physical and mental challenges that include elements of speed, height, depth, or natural forces. Orth et al (7) proposed that rather than ideation leading to creative action, in extreme sports, creative actions are more likely to emerge as the action interacts spontaneously with task-environmental constraints. A zone of meta-stability is often achieved in which a system is poised between states of order and instability (8). In direct association with this is the reality that injury or fatality is more likely to occur than in a non-extreme sport.

In recent years, extreme sport participation rates have increased faster than many traditional sports (9). Extreme sport participation may develop a profound athlete-environment relationship that can potentially enhance psychological and physical well-being and health (10). Extreme sport athletes may be searching for high risk experiences involving elevated levels of sensation, physiological arousal, and novelty (11). They have also been described as self-confident and optimistic individuals who are more likely to attribute accidents and fatalities to internal characteristics rather than to external circumstances (12), while often underestimating their personal risk of being injured (13). Risk-centric interpretations of extreme sport participants may be too superficial (1). Of considerable importance may be the development of a profound person-environment relationship that can potentially offer a variety of ways to enhance psychological and physical well-being and health (14,15). Many extreme sport athletes may also pursue higher-level motives such as goal achievement, mastery-seeking, defeating monotony, self-discovery, social motivation, natural environment connections, time for peace and reflection, feeling of pleasurable bodily sensations, and achievement of unselfconsciousness (16-17). Experiencing fear can also be a potentially meaningful and constructive event in the lives of extreme sport athletes. Having a better understanding of the implications of fear as a potentially developmental and transformative process is important when treating extreme sport athletes (14). Likewise, emotions such as anxiety, excitement and pleasure, as well as beliefs, values and motivations possess significant roles during extreme sport participation and have a strong influence on an individuals' environmental perceptions (18). Participation in extreme sport can be a way to strive for self-actualization, self-discovery and to develop new coping mechanisms (2,15). Individuals who are self-actualized possess a greater sense of self-acceptance and thrill for living for the moment, with the mind and body acting in unison (15,19). Extreme sports participation has been described as being ineffable edgework, suggestive of emerging subcultures or neotribes, existential reflection or self-actualization (14).

Robinson (20) viewed extreme sport as an activity based on both cognitive and emotional components, such as, "a variety of self-initiated activities that generally occur in natural environment settings and that, due to their always uncertain and potentially harmful nature, provide opportunity for intense cognitive and affective engagement" (**figure 1**). Similar to this is the flow concept described by Csikszentmihalyi (21), in which the conscious state becomes completely absorbed into a situation or sport. The sense of elation and peace experienced in extreme sport may be the result of the endogenous mood enhancement provided by a combined adrenalin rush and endorphin release (2). Linked with this may be the need for the extreme sport athlete to escape the mundane boredom of daily tasks or living in a risk-free comfort zone through outlets where the self and reflective thought can be rediscovered (15,22). The majority of extreme sport athletes are between 15-44 years of age (23) with an average of 30-31 years (2). Therefore, another essen-

Figure 1. Surfer-wave, athlete-environment interaction "in the flow" (21).

tial factor may be the transition from adolescence to adulthood, as a modern rite of passage, given the uncertainty of approaching adulthood and issues related to work, family and finances (2,15,24). Extreme sports may be better than traditional sports for encouraging lifelong wellness (14).
Equipment needs and individual body mechanics vary between different extreme sports, as do potential injury risks and injury mechanisms (25). For example, while the knee is the most commonly injured body region among extreme sport skiers, the wrist and ankle are more often injured among snowboarders (26). Most traumatic skate- or snow-boarding injuries involve teenage boys older than 16 years of age (27,28). More surfing injuries occur in men in their late twenties (29). Most base jumping injuries occur in single men in their thirties, with most participants having witnessed the death or serious injury of another participant (30). Whitewater paddle sportsmen who sustain serious injury tend to be of similar age and gender (31); however, commercial whitewater rafters display equal gender distribution (32). Having an unsuccessful outcome in an extreme sport is more likely to result in severe injury or even a fatality (26). It is not uncommon for a wingsuit athlete to have known someone who died suddenly from a collision while performing their sport. For purposes of ameliorating risk in sports that have a high death risk, it is important that clinicians develop a sound understanding of the actions or inactions that may have preceded the tragic event.

The expanded specific adaptations to imposed demands (SAIDS) principle

The Specific Adaptations to Imposed Demands (SAIDS) principle of training suggests that the human body adapts specifically in response to the neurophysiological and, perhaps, psychobehavioral inputs to which it is subjected (33,34). Optimal athletic performance is achieved through complex three-dimensional coordination of the muscles, connective tissues and nervous system throughout the kinetic chain. A fundamental attribute to complex dynamical systems is that they must continuously adapt and change their organizational states (35). This is characterized by emerging coordination between system components or degrees of freedom and by synergetic relations between individuals and the environment in a manner that more effectively translates integrated axial and appendicular body function (36). It is crucial that extreme sport athletes align these coordinated efforts with environmental conditions, gravitational forces and natural energy sources such as wind and water. During extreme sport performance, environmental constraints may never remain truly fixed from one moment to the next. For extreme sport athletes, the SAIDS principle of training needs to place greater emphasis on linkages between psychobehavioral, sociological, and emotional considerations with physical, mental, cognitive, and environmental factors. Rehabilitation clinicians need to better understand the ideal, likely and worst case scenarios for any given extreme sport both from the perspective of the athlete, sport partners, teammates, and support crews. As important to environment conditions and task skill is an individual athlete's personality characteristics, which not only affect the rehabilitation process, but also the predicted outcome (37-39).

Ecological dynamics

Immonen et al. (40) proposed that ecological dynamics represented a holistic, comprehensive framework for defining extreme sports participation. The ecological dynamics approach to perception, knowledge, action and skill acquisition involves a process where an existing repertoire of behavioral capabilities (or coordination repertoire) are destabilized prior to being re-organized through effective practice. When done correctly, this process can expand the athlete's affordance boundaries, enabling them to explore new environments (36). Key ecological dynamic factors include skillful behaviors that involve athlete-environmental interactions, the timely processing of perceptions that drive action strategy and tactic development, and how performance behavior modifications occur over time based on interacting constraints (1). Strategy represents the operational plan an athlete uses to achieve a particular goal or aim (climb to the summit, win, have fun). Tactics are the specific actions, means or methods the athlete uses to achieve the strategy they have selected. Having a sound understanding of these factors and how synchronously they link, given the athletes experience, skill, personality, conditioning, and injury recovery status, is essential to the rehabilitation clinician. Within this context, constraints represent the temporary boundaries that shape the emergence of each athlete's developing cognitions, actions, and decision-making processes. Constraints may include, but are not limited to, factors such as knowledge, skills and technical abilities, conditioning level, injury, surgical or medical history, capacity to tolerate pain, motivations and perceptions (41). As extreme sport athletes adapt to changing conditions or unpredictable natural and social environments, they must develop a sound understanding of their individual constraints within the context of task performance and environmental conditions (1). For a high injury risk sport such as BASE jumping, concerns exist regarding participant training level, discipline (i.e. tactical and strategic decision-making efficacy) and control (17). Adequate preparation requires participants to possess sport knowledge and understanding of the unique characteristics of the location where they plan to perform the activity, the environmental conditions and especially, themselves (17). Ecological dynamics integrate ideas from dynamical systems theory and psychology toward the achievement of better adaptive learning and behaviors in any particular environment (40). Rehabilitation clinicians should understand that in an effective therapeutic exercise environment self-organizing global system order best emerges when the patient's own system dynamics are challenged by instantaneous disorder (42) (**figure 2**). The effort to satisfy existing performance constraints gives rise to perceptual neuromotor couplings that support and optimize the extreme sport athlete's perception of action affordances or opportunities (43). By learning new ways to adapt to novel situations, the extreme sport athlete experiences movement system degeneracy prior to developing newer, more efficient functional solutions (44). This process helps extend the boundaries of what their environment affords for action (7). During guided rehabilitation, temporary task instability facilitates exploration of alternative movement solutions and hence, adaptability (45). Rehabilitation clinicians should help guide and shape extreme athlete responses by manipulating constraints and affordances so that the athlete in training learns varied task solutions without presuppositions, even when confronted with sudden perturbations or chaotic situations (38,46). Movement adaptability combines task exploration, enhanced degeneracy and discovery of new, adaptive, functional answers that support the expansion of affordance boundaries or the "comfort zone" (47). With practice, individuals can develop new, more refined adaptive movement coordination patterns.

In team sports such as soccer or basketball, constraints are directly embedded within game rules. In contrast, extreme sports are usually free of organizational rules and regulated competitive frameworks. Environmental constraints may be related to physical phenomenon such as weather, temperature, gravity, surface friction, buoyancy, vision, oxygen level, etc. and/or sociocultural factors such as values or norms that influence perception, family or peer support (43) (**figure 3**). The rehabilitation clinician experiences similarly complex decision-making situations when train-

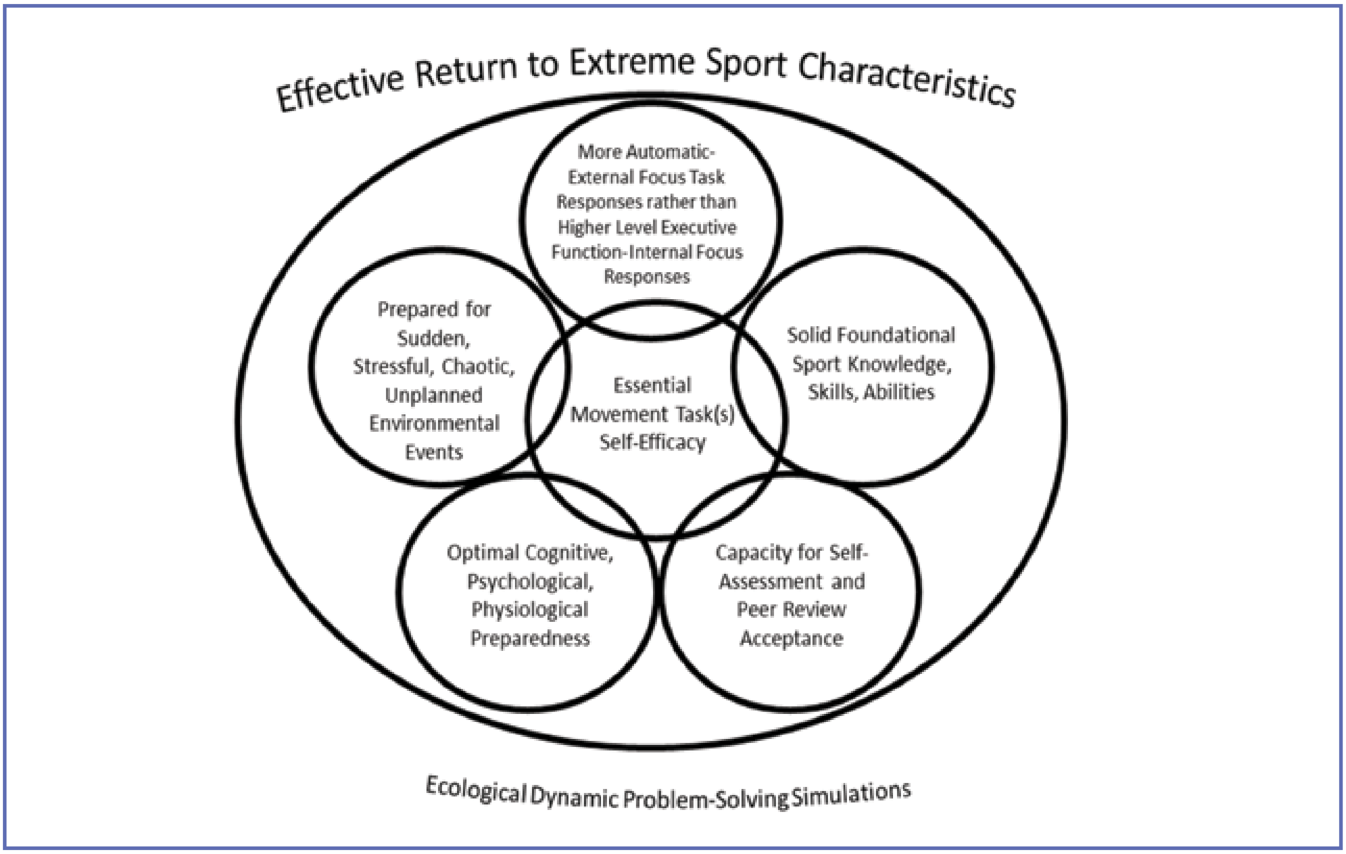


Figure 2. Improving the rehabilitating extreme sports athlete's self-organizing systems.

Figure 3. Young climber with multiple climbing wall route options, exploring to expand the comfort zone.

ing and evaluating these athletes. Given the uniqueness of each extreme sport environment, game-based virtual reality training simulations similar to those used with military jet pilots, law enforcement, or military special forces training might be integrated into strategic and tactical training to obtain objective spontaneous decision-making effectiveness measurements to better validate the needed cognitive processes. In agreement with the SAIDS Principle, rehabilitation programs should consider the specificity of loading force magnitudes, application points, velocity, variances, the impact of sudden unplanned, random or chaotic events in relationship to the time needed by the athlete to effectively react with the necessary motor plan adjustments required to restore psychophysiological homeostasis. Upon returning to extreme sport activities, it is essential that the athlete maintain a reflective journal that documents their subjective perceptions of performance, skill level or general conditioning strengths, weaknesses, training or safety needs that might require more dedicated attention during practice or training in addition to environmental factors. This self-assessment should then be integrated with information obtained through peer assessment by sport colleagues who have comparable or greater skill levels.

Training to return-to sport decision making

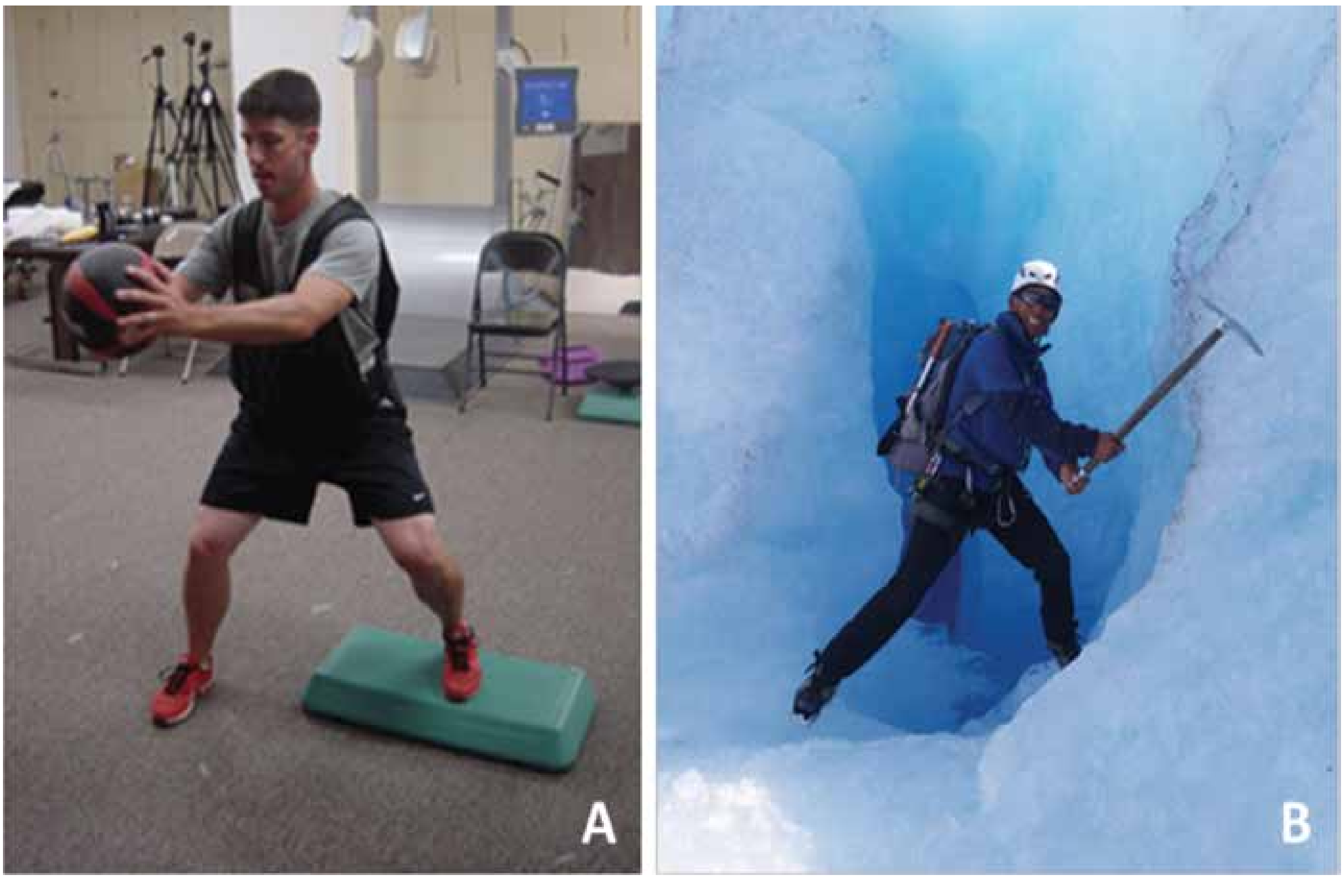
Interactive educational programs and workshops are effective in reducing injury risk, collisions, and falls in novice skiers and snowboarders, while one hour educational workshops have been shown to be beneficial to more advanced participants (48). Valid appraisal of the extreme sports athlete as possessing beginner, intermediate, advanced, or expert skills is an essential part of the return to sport decision making process. Prior to the return-to-sport decision making, it is important that the rehabilitation and medical teams evaluate performance and injury prevention readiness with consideration for the ability of the extreme sport athlete to realistically self-appraise strengths and weaknesses. This is particularly important when confronted with stressful, unexpected, challenging situations such as rapidly changing weather conditions, unstable or slippery surfaces, limited vision, or sudden perturbations.

Extreme sport performance represents the intersection between athlete-environmental coupling and complex, emergent system self-organization adaptations (49). Training of specific movement tasks under progressively more difficult, functionally relevant conditions can increase athlete self-efficacy as has been shown with other forms of musculoskeletal rehabilitation (50).

Rehabilitation clinicians should guide the extreme sports athlete toward movement creativity and adaptability by encouraging exploration. To better develop adaptive behaviors, environment manipulation may be needed to place the athlete outside of their comfort zone. This process is enhanced through added noise such as perturbations, unstable surfaces, reduced vision and use of a more external than internal task focus. In this non-linear, learner-centered approach to skill acquisition, the rehabilitation clinician serves more as a functional movement designer/architect rather than a drill sergeant-focusing on the guided exploration of opportunities or affordances of action (49). Training relevance and validity can be enhanced by manipulating the environment from both an internal and external performance perspective and changing the context within which timely decisions must be made when confronted with unplanned or chaotic events. Movement paths variability should not be considered a lack of optimization, but rather, an essential factor to developing multiple problem solutions, expanding the zone of safe functional possibilities. By holding devices or tools in the hands when training, integrated core-extremity coordination can be developed in a manner that better prepares the athlete for actual environmental conditions (51) (**figures 4A, 4B**). Extreme sports techniques and use of innovative technologies continue to evolve. For example, pioneers of extreme sports such as surfing and wingsuit flying have adapted their sports through the use of jet skis to access larger waves, and suit airfoil designs to enable better horizontal flight and glide proximity flying maneuverability (52). Extreme sports are often more directly connected to technological innovations that drive performance than traditional sports. Rehabilitation clinicians need to be equally vigilant in designing return to sport training programs and evaluation methods to accommodate extreme sport strategic and tactical plan modifications. Although primary injury prevention strategies are essential for all sports, secondary injury prevention strategies should be stringently embedded in the return to play decision-making process for most extreme sports, as a secondary injury is more likely to be associated with major trauma or sudden death to the athlete or to their partner, teammate or support team.

Developing extreme sport-specific rehabilitation key task assessment criteria

Return to extreme sports training post-injury or surgery requires that the rehabilitation clinician has a thorough understanding of the extreme sport, the index injury mechanism(s), the athlete's knowledge, experience, skill level, personality and the potential influence of environmental factors. Consolidation of factors such as these, in addition to knowing the extreme sport athlete's reason for participation (to summit, to win, to achieve better quantitative or qualitative scores, to feel self-actualized, etc.) and capacity for handling stressful, unplanned events set the stage for more prescriptive training and guidance. Use of a variety of unstable training surfaces such as wobble boards, Swiss or Bozu ball, with or without single leg or arm support, can simulate the unsteady natural surfaces associated with many land-based tasks (**figure 5**). Use of blind folds, vision blocking goggles, or dark rooms can provide the exteroceptive deficit needed to elicit optimal somatosensory system responses within the confines of a clinic or performance training area.



Figures 4A and 4B. Use of a medicine ball during whole body lunge – long axis rotational movement (A) improves athlete preparedness for tool use during extreme sport performance (B).

Figure 5. Whole body mobility (A), on an unstable surfaces (B), adding the core to isometric dumbbell work (C-E).

Specific key movement task subcomponents or unexpected events such as sudden single leg support requirements, multi-directional near falls, reverse falling and equipment failure scenarios can be integrated into task problem-solving scenarios, where both the extreme sport athlete's movement quality and ability to master functional puzzles or dilemmas in a timely, efficient manner are assessed. Within this context, the rehabilitation clinician should include a variety of situational scenarios related to key aspects of performance cognitive decision-making. Given the strength, power and endurance requirements of each sport, both central and peripheral fatigue should be included as training stimuli. Naturally undulating slopes or elevated treadmill hikes with sudden acceleration-deceleration and changing terrain intervals, in combination with weighted vest, dumbbells or resistance bands performed over repeated sessions with reduced recovery time can improve simulation validity and fatigue tolerance. It is also important to mention that the extreme sport athlete who performs with partners or teammates should be sufficiently fit, and fatigue resistant, to not just care for themselves in serious conditions, but also to develop the reserve to be able to oversee the care of partners or teammates who may have succumbed to injury or illness (**figure 6**).

Continuous performance improvement through guided practice may be more likely to occur in extreme sports athletes who do not need to dramatically modify their existing overall movement patterns, but rather, just need to refine them to more effectively achieve the desired outcome (53). Alternately, individuals who display sudden performance improvement may display greater behavioral variability during learning-suggesting that the newly learned behavior is

Figure 6. Mountaineering team ascending a Himalayan mountain slope.

initially unstable. Lastly, in situations where an extreme sport athlete does not improve through practice, the task dynamics may be too complex relative to their current skill level. In this case, a transitional, new behavior may not surface, possibly preventing them from achieving the task goal, even after extensive practice. Individuals also may not improve because they do not have sufficient physical or mental skills to explore effectively. Exploration is a necessary ingredient for learning behavior improvement to occur, uncovering the transitional information needed to support a new movement coordination mode. In climbing, because of the added elements of altitude, slope and injury risk due to falling, facilitating safe exploration is particularly important (54). Indeed, if an individual feels unsafe when climbing, they will have more restricted movements leading to ineffective task exploration. Movement restrictions following knee joint surgery are known to be problematic and should be overcome to prevent re-injury. One of the key challenges to the rehabilitation clinician is to appropriately scale task difficulty relative to the individual learner over time. Subsequently, the rehabilitation clinician should identify constraints that best influence the extreme sport athlete's stability as they search for ways to achieve fluent successful new movement patterns.

Psychological return to sport evaluation considerations

Psyche and emotion are directly related to task performance decision-making and this often contributes directly to safety and outcome success (55). For this reason, athletes that engage in high risk sports likely need more varied, novel, and complex sensorimotor experiences during rehabilitation to perceive validity and therapeutic exercise task relevance. Extreme sport athletes may also be more likely to use active coping strategies during rehabilitation (54). Return to sports decision-making for the extreme sport athlete requires an appreciation for the possibility of underlying stress perceptions, fear avoidance, health locus of control, task specific self-efficacy, and kinesiophobic characteristics. Extreme sport athletes may also be more likely to ignore medical or rehabilitation advice and continue with potentially destructive behaviors post-intervention (39). Cohen et al (37) identified a significant difference in the level of neuroticism (i.e. anxiety, worry, fear, anger, frustration, envy, jealousy, guilt, depressed mood, and loneliness) with regards to athlete skill level. Eysenck et al (56) reported that neuroticism was lower in professional athletes compared to amateurs and Cohen et al (36) confirmed this claim with professional drag racers and professional archers scoring lower in neuroticism than amateur athletes.

SUMMARY

Rehabilitation clinicians need to consider multiple factors during post-injury or surgery return to sport decision-making to effectively treat extreme sport athletes. Factors such as experience and skill level, personality, conditioning level, overall health and injury status and the injury risks associated with many extreme sports makes this process particularly difficult. Through sport movement-specific affordance and constraint manipulation, the rehabilitation clinician can guide and shape the learning needs and fatigue tolerance of extreme sport athletes to develop variable movement solutions to better adapt to environmental challenges. Return to sport decisions should represent a team effort between the athlete, medical and rehabilitation team. Research is needed to develop the best holistic approach to capturing the essential physiological, psychological and perceptual information needed to guide this process and to develop specific criteria for differing sports.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (57).

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ORIGINAL ARTICLE

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Protective and Supportive Garments and Bracing to Enhance Extreme Sport Performance and Injury Prevention

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SUMMARY

Background. Protective and supportive trunk, limb and joint garment or brace use to enhance performance and prevent injury among extreme sport athletes is evolving.
Methods. This review discusses protective and supportive trunk, limb and joint garment or brace use from the perspective of the essential mental and physical demands of extreme sports with special consideration for improving capsuloligamentous, musculotendinous, and myofascial system function.
Results. Bracing to protect or support, preserve and promote natural joint function is evolving from the use of heavier, rigid, over-constraining and poorly fitting devices to lighter, more flexible, lower profile, function-enhancing garments or braces. Therapeutic exercises that combine task-specific self-efficacy and problem-solving skill development may best optimize innovative protective and supportive trunk, limb and joint garment or brace use.
Conclusions. Through greater surface contact area and enhanced cutaneous, capsuloligamentous, musculotendinous and myofascial system mechanoreceptor function, a new evolution of protective and supportive trunk, limb and joint garments or braces may be better able to effectively facilitate more natural joint protection, proprioception/kinesthesia and dynamic stability.

KEY WORDS

Experiential rehabilitation; adventure sports; therapeutic exercise.

INTRODUCTION

Given the dynamic environments in which extreme sport athletes perform, adaptability and creativity are needed when rehabilitation clinicians provide guidance about protective and supportive trunk, limb and joint garment or brace use. Similarly, rehabilitation clinician interactions should consider environmental demands, the unique needs of the rehabilitating extreme sport athletes and the specifics of essential task performance. Task performance parameters should be manipulated from physical, cognitive and environmental perspectives (1). To best refine participant judgement and decision making, it is important that the extreme sports athlete is an active participant in the learning experience (1). Through soft tissue mobilization, massage, and stretching techniques, myofascial tissue have become a growing rehabilitation treatment intervention focus. Altered coordination, proprioception, balance, pain levels, and cramping are often associated with the deep fascia and epimysium, as they influence muscle, nerve, blood vessel, and organ functions (2). In contrast, the superficial fascia is more often associated with lymphatic and superficial vein circulation and thermoregulatory functions.

Athletes can display addiction-like behaviors (3). These behaviors often lead them to devote continually increasing time and monetary resources to perform their preferred sport sport at higher skill levels, with progressively greater injury risks (4). In addition to the increased injury risk associated with extreme sport participation, when these athletes are prevented from sport participation because of defective, restrictive, or poorly fitting equipment, they may suffer emotional or mental distress with powerful physiological and psychological symptoms (4). Therefore, the functionality, durability and ease of use of recommended protective and supportive garments or braces is essential to use adherence.

MENTAL AND PHYSICAL DEMANDS

The demands of climbing and abundance of both psychological and physiological data (5) makes it an intriguing model for discussing the potential rationale for supportive and protective garment and brace use. Climbing intensity increases from either greater upper limb muscle engagement or greater whole body effort (6). Increased climbing route difficulty redistributes the workload to smaller muscle groups, particularly in relationship to grip-surface reductions (6). Climbing research has focused primarily on its physical requirements, placing little emphasis on its cognitive, psychological and behavioral aspects (7). Climbing, like many other extreme sports, incorporates strong physiological and psychobehavioral links (6,8,9). Climbing not only requires a profound understanding of how to recognize and interpret environmental constraints such as weather conditions (temperature, humidity, wind velocity, etc.) and rock, ice or other surface characteristics, but also requires instantaneous adaptability and highly tuned skills (10) (**figure 1**). In this context, when protective and supportive garments and braces are used, they must adapt instantaneously to changing environmental conditions and not negatively influence the climber's ability to perform skillful movements.

Combined mental and physical climbing demands, in combination with exercise-induced central and peripheral fatigue, increases heart rate, cortisol and lactate concentrations (8). Magiera et al (6) studied athletes under high, moderate, and low physical and psychological demand climbs. They identified lower physiological demands with climbing route familiarity and the performance of single moves of comparable difficulty. Physical exercise exerts considerable salivary cortisol concentration increases, when exercise intensity exceeds 60% VO_2 max or lasts at least 20-30 min (11). Cortisol levels increase within 10 minutes and reach a maximum at the 10^{th} to 30^{th} minute after stress cessation (12). Similar cortisol concentration increases have also been reported for downhill mountain biking (13). Magiera et al. (6) reported that three repetitions of a difficult climbing route with a short recovery time increased post-climbing cortisol concentrations. The highest cortisol levels were observed immediately following climb descent. Even anticipation of stressful experiences cause sympathetic nervous system and hypothalamic-pituitary-adrenal axis activation, resulting in cortisol release (12). Selected protective and supportive devices also should not contribute to heightened climber stress levels.

When exercise intensity exceeds the anaerobic threshold, lactate accumulates in skeletal muscle, resulting in decreased intramuscular pH (14). Lactate removal can be improved by increasing blood flow to other body parts and enhancing its oxidation through greater use of previously inactive muscles or other organs such as the liver (15). Intense or prolonged forearm muscle activation increased lactic acid concentrations, while aerobic metabolism across greater muscle mass improved its clearance. Blood lactate concentrations after rock climbing are lower than cycling because of the smaller total muscle mass that is exercised (16). During treadwall climbing until exhaustion, maximum blood lactate concentrations are higher (10.2-11.1 mmol/l) (17) than during actual climbing (< 6.8 mmol/l)(18). The aerobic and anaerobic alactic systems are the primary energy systems used during indoor rock climbing (19). When climbing wall angles exceed vertical, grip strength decreases and blood lactic acid concentrations significantly increase (20). Magiera et al. (6) found that peak heart rate was the most sensitive mental and physical stress level and workload measurement among rock climbers. Protective and supportive devices should not restrict the circulatory function necessary for lactic acid clearance and active recovery.

Seifert et al. (21) showed that more experienced climbers used more diagonal hip positions relative to the climbing wall when using holds that necessitated a side-on coordination pattern. Experienced climbers also had a larger

Figure 1. Environmental conditions, equipment needs.

movement pattern repertoire so they could better adapt to constraints as climbing hold orientations changed. The learner's movement intentions are, in some ways, determined by their pre-existing coordination repertoire. The way an athlete explores and learns a new task is influenced by the number of movement solutions that they possess under an already experienced existing set of constraints (22). Implications for extreme environment climbing are that climbing walls with planned route variability can provide effective learning contexts for movement skill development when they are accompanied by opportunities that enhance environmental knowledge and decision-making skills. Safely exploring new movement coordination patterns and the complex alignment of cognitive and sensorial experiences is paramount to extreme sport performance adaptations and safety (23). While protecting or supporting a specific joint or body region, the selected brace or garment should not adversely affect adjacent joint function or otherwise restrict the climber's ability to assume essential positions.

SYNERGISTIC TRUNK, LIMB, AND JOINT MYOFASCIAL SYSTEM ENHANCEMENT

Muscle fibers are contractile components of a functional complex that is inseparable from its parallel and series non-contractile fibrous components. Activated muscle forces depend not only the anatomical structure of the muscle or muscle group, but also on the angle at which its fibers attach to intramuscular connective tissues, the epimysium and the deep fasciae (24). Fascia is an elastic tissue with established extensibility limits that effectuate motor coordination, movement perception and postural variation signaling (25). The endomysium, perimysium, epimysium and deep fasciae are fundamental to muscular force transmission, with each tissue possessing a specific role (24).

The myofascial system originates proximal to the upper and lower extremities to provide both joint and extremity protection, containment and stability. Neurophysiologists support the presence of a peripheral movement coordination system activated through gliding fascial layers (26). The brain interprets movement as three-dimensional agonistic synchrony during spatial movement task performance, not as independent muscle actions (27). Located within high muscular traction zones are densely innervated myofascial coordination centers (26). Through its basal tension, myofascial structures help maintain appropriate body posture. Acute injury or chronic inflammatory conditions at these centers can densify the tissue with unorganized collagen fibers, leading to pain. The body neutralizes this pain by adopting a compensatory, maladaptive posture to better

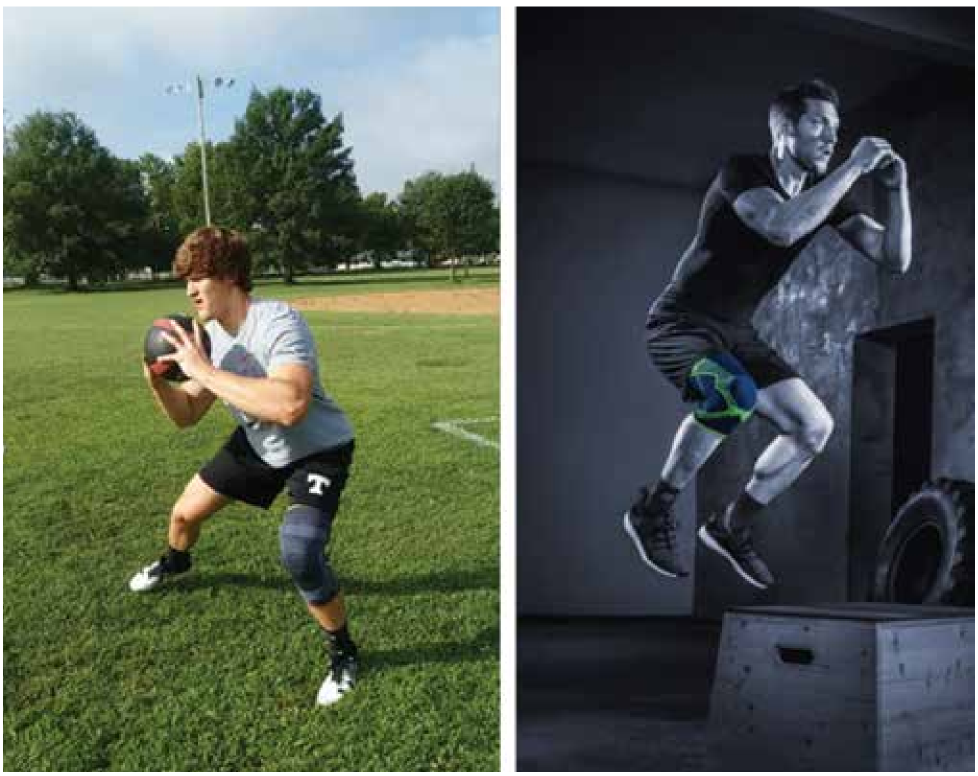

Figure 2. Evolving knee brace designs (A. Genu Medi Pro Knee Support; B. E + Motion Soft Support).

re-establish basal tension. During healing, newly developed collagen fibers can only align themselves along the normal segmental force lines when normal basal myofascial tension exists (26). Myofascial system activation during movement can vary from individual motor units to multiple myofascial unit sequences across adjacent joint segments. To better engage myofascial system synergies, innovative protective and supportive garment or brace interfaces are being developed that blend compressive fit with embedded diagonal straps, mediolateral hinges, physiological monitoring (position, temperature, force, etc.) and region-specific capsuloligamentous, musculotendinous and myofascial augmentation to provide protection or support without over-constraint (28,29) (**figure 2**). Many of these products attempt to combine the positive attributes of conventional garments and braces with athletic and kinesiotaping concepts that enhance proprioception/kinesthesia and natural myofascial system gliding function (**figure 3**). In association with this, fasciacytes produce hyaluronan to reduce friction, improving fascial mobility and decreasing myofascially-mediated pain (30). Stecco et al (31) reported that the gluteus maximus - fascia lata attachment was so large that the iliotibial tract was effectively its tendon of insertion. Thoracolumbar fascia forces can be transmitted from the gluteus maximus to the knee and from the latissimus dorsi to the shoulder. Painful patellar tendon conditions often occur from uncoordinated muscle or muscle group activation in the presence of anomalous myofascial tension (26). For these conditions, the treatment focus should not be at the local site of tendon pain, but rather it should be directed toward identifying the location of the myofascial incoordination (32). Myofascial continuity between the thoracolumbar fascia-abdominal muscles and the erector spinae – rectus abdominis also helps ensure dynamic postural trunk stability (33).

The supplemental limb and joint protection and support that used to be exclusively dependent on external brace use, now may at least partially be provided through innovative surgical internal bracing or supplemental extra-articular soft tissue repair (34). When feasible, surgical internal bracing may better facilitate capsuloligamentous tissue repair, concurrently retaining proprioceptive elements commonly lost during ligament reconstruction or joint replacement. Greater use of less rigid, functionally firm, protective and supportive garment or braces might be analogous to the contrasting properties of anatomical surgical repair versus reconstruction. Through more distributed surface contact area, these devices may enable better cutaneous, capsuloligamentous, musculotendinous and fascial mechanoreceptor function for dynamic joint stability than rigid braces, without reducing joint range of motion or impairing neuromuscular and neurovascular function. These

Figure 3. T-25 thigh compression garment to enhances dynamic knee control (CEP Topical Gear).

evolving supportive and protective garments or braces are being designed in concert with growing efforts to preserve joint health whenever feasible through more anatomical and biological surgical and non-surgical joint repair, rather than reconstruction. Impaired ACL injury neurosensory proprioception combined with ipsilateral rigid brace use may be related to the increasing frequency of contralateral, non-contact knee ACL injuries that have been observed. Use of regenerative biological healing progenitors such as stem cells, plasma-rich in platelets, or amnionic membrane tissue represents a developing and exciting contemporary healthcare sector. Innovations like these challenge rehabilitation clinicians to carefully determine the best combination of progressive joint loads, sport movement-based therapeutic exercises, and garment or brace use to accelerate both tissue healing and motor learning. This will ultimately result in more functionally responsive neuromuscular activation patterns and remodeled tissues that more closely match premorbid histology, morphology and biomechanical characteristics.

FOOTWEAR AND GLOVES

The combination of feet pushing against the ground (**figure 4**) and the arms pulling generates holistic energy transfer throughout the entire body. Because of the close relationship between shoe-surface interactions and injury risk, footwear outsole configuration and its influence on locomotor traction is the most studied athletic footwear parameter (35). Cleats without studs provoke more vertical lower leg alignment at running stance phase initiation in combination with lower ankle and knee joint moments (36). Soft ground interfaces decrease foot movement in combination with increased ankle and knee moments (36). Extreme sport athlete footwear considerations should balance the increased primary and adjacent torsional joint injury risk associated with footwear stud use and the potential for injury from increased slipping risk without their use (35, 36). Use of shorter, stubbier cleats have been recommended to prevent football knee injuries (37). Across a wide range of traditional and extreme sports, specialty gloves have been developed to enhance hand and wrist joint protection and support, touch perception, grip strength and proprioceptive awareness (**figures 5**). Sports that necessitate direct skin contact such as climbing often use more traditional athletic taping techniques to enhance joint stability without compromising fingertip sensory grip perception.

Figure 4. Climbing shoe – hold interface.

EVOLVING PROTECTIVE AND SUPPORTIVE GARMENTS AND BRACES

Bracing to protect or support, preserve and promote natural joint function is evolving from the use of heavier, rigid, over-constraining and poorly-fitting devices to lighter, more flexible, lower profile, function-enhancing garments or braces. This evolution is intended for three-dimensional protection, while not generating maladaptive primary or adjacent joint kinematics, or impaired/inhibited neuromuscular activation, neurovascular function or altered peak joint forces. Conceivably, protective and supportive garments or braces such as these may also provide a better foundation for enhancing cutaneous, capsuloligamentous, musculotendinous and myofascial system proprioception/kinesthesia and dynamic joint stability (**figure 6**). With a growing appreciation for the importance of peripheral, non-contractile joint stabilizers such as the anterolateral knee ligament (38), posterolateral and posteromedial corner knee and antero-inferior shoulder capsuloligamentous tissues (**figure 7**), rehabilitation clinicians are seeking better ways to enhance

Figure 5. Hand-wrist supports. A. finger pulley taping; B. wrist and thumb stabilization; C. proprioceptive-gripping; D. full hand-wrist protection.

Figure 6. Wall climbing wearing compressive calf sleeves.

dynamic joint stability with improved patient comfort and use compliance. Athletic footwear has also evolved away from rigid, high motion control shoe designs to more preemptively protect and control the ankle, subtalar, transverse and longitudinal arches and first metatarsophalangeal joints, without the overconstraint that transfers loading forces proximally to the knee, hip and low back. The growing use of low movement control shoes in an attempt to modify running mechanics toward more forefoot-directed contact patterns with greater intrinsic core foot muscle use may help mitigate the influence of excessive, poorly controlled knee and hip joint loading forces.

Sleeve-based protective and supportive garments or braces have the advantage of simpler, quicker application, avoidance of piston-like positional changes that lead to slippage during joint movements and easier adaptation to neuromuscular inhibition/atrophy and activation recovery/hypertrophy limb girth changes. Protective and supportive garments or braces can also be more easily integrated into compressive sport shirts, shorts and leggings with or without additional orthosis use (28,29).

Therapeutic exercises that combine task-specific self-efficacy and problem-solving skill development may best optimize innovative protective and supportive garment or brace use. Given the variety of movements that come under the extreme sport definition, appropriate therapeutic exercise selection or creation provides an ideal method for the athlete to learn from, "if this, then that," situations and scenarios to simulate the sport-specific movements needed to optimize joint specific, regional, and whole body coordinated neuromuscular, sensorimotor, and vestibular system protective responses. Well-designed movement-based task- and sport-specific therapeutic exercise programs should more effectively transition from higher level, executive cognitive function with careful attention to developing movement quality and form to lower level, automatic responses

Figure 7. Glenohumeral joint support using the DonJoy Sully Shoulder Stabilizer.

as the athlete is confronted with random perturbations or unexpected chaos. To better enable healing tissue remodeling, whenever feasible, the extreme sport athlete should periodize protective or supportive garment or brace use. As with the stress shielding of cast immobilization and limited weight bearing crutch use, biomechanically competent tissue healing only promotes tissues remodel in response to progressively greater natural joint loading conditions.

Rigid braces will always have a vital role in athletic rehabilitation and recovery, such as when repetitive or higher energy contact or collision risks can be expected (downhill skiing, American football) or when high joint movement or alignment constraints are needed. These supports may also be the ideal intervention with treating the extreme sport athlete who has sustained a severe multi-ligament bi-cruciate or cruciate-corner knee injury, when natural joint kinematics have not been precisely restored, when articular incongruency (step-off) remains, when osteoarthritic joint changes exist, or when chondral surface repair or reconstruction warrants off-loading or re-alignment osteotomy.

SUMMARY

Through greater surface contact area and enhanced cutaneous, capsuloligamentous, musculotendinous and myofascial system mechanoreceptor function, a new evolution of protective and supportive trunk, limb and joint garments or braces may more closely simulate the subtle, sequential natural protection and proprioception/kinesthesia and dynamic joint stability

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (39).

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ORIGINAL ARTICLE

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A Systematic Review of Smart Clothing in Sports: possible Applications to Extreme Sports

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SUMMARY

Background. Traditional monitoring of athletes during sports has long been hampered by bulky, complicated and tethered systems. In the past decade, this has changed due to the miniaturization of sensors and improvement of systems to store and transmit data. These systems have been integrated into textiles to create 'smart clothing' which has been so ubiquitous that a review of the recent literature is crucial for understanding its full potential and potential use in extreme sports.
Methods. An electronic data base search was performed from 2003 to April 2019 for full length articles including "Smart" AND "Clothing" OR "Clothing" AND "Sport(s)" written in English with human subjects. Articles were evaluated according to the Newcastle-Ottawa Scale.
Results. Twenty-four studies resulted in 18 systems comprised of 22 types of clothing with various capabilities, including: monitoring heart rate, electromyography, respiratory rate, steps, GPS, energy expenditure, posture, body temperature and identifying the activity.
Conclusions. Many types of smart clothing from socks and gloves, to pants, shirts and bras are increasingly utilized to monitor sports activity worldwide and gather previously unavailable, yet highly valuable data. This provides a unique opportunity to study athletes during training and competition, potentially providing more effective training and better safety protocols.

KEY WORDS
Smart, clothing, sensorized, textiles, sport, extreme.

INTRODUCTION

Until recently, monitoring athletes during competition or training has been difficult, if not impossible, due to the systems used. Traditional methods for studying athletes were once restricted by the need of the systems to either be connected to power, or for the sensors to be directly tethered to the processors, which kept many studies limited to laboratories rather than performing experiments in the field of play. Additionally, many of these systems were bulky and restrictive, which inhibited athletes from performing as they normally would. In recent decades however, advancements in textiles and sensor technology have led to the creation of sensorized garments as an alternative to uncomfortable, tethered systems. Innovations in sportswear have resulted in new, sport-specific textiles compositions for improved aerodynamics, stimulus-responsive polymers and aerogels, and specialized coatings for thermal and perspiration management (Rossi et al, 2018). Simultaneously, sensors have been reduced in size and integrated into these specialized textiles to make "smart clothing." Smart clothing allows athletes to perform their sports unencumbered while physiological (heart rate, respiration), performance (posture, movement), and environmental (temperature, humidity) data are acquired in real-time (Lam Po Tang et al., 2015). This is particularly advantageous in extreme sports where athletes commonly make rapid decisions and acrobatic movements in adverse environments and any interference could be potentially dangerous.
Smart clothing systems have increasingly levels of complexity and capability which is commonly classified in three different categories: passive, active and ultra-smart textiles. Passive smart garments can only perceive the data

from the human body or the environment such as step count, calories or heart rate. Active smart fabrics involve both sensors and actuators like stretch sensors are elastic bands that include soft capacitors, which when stretched, provide reliable data about human body motion (Koncar V, 2019). Finally, ultra-smart garments can sense, and by means of integrated microcomputers, intelligently elaborate diverse data types in order to make predictions and respond to external requirements. For example, spacesuits are able to thermoregulate the human body, depending on the environmental temperature (Pailes-Friedman, 2016). Some of these systems are made even more effective by also incorporating radio-frequency identification (RFID) chips in the textile constructions to both sense and transmit data wirelessly transmitted, known as telemedicine (Joyce 2019; Gaddis, 2014; Syduzzaman, 2015, Di Rienzo et al., 2010). This offers functionality in a diverse range of previously unavailable environments and also means that athletes do not need to sacrifice training time to perform experiments.

Due to the capabilities of smart clothing, many applications have been proposed including training, competition, recovery and even safety. Lam Po Tang (2015) states that real-time biofeedback can be used to provide input on improving movement and reducing human error. By gathering data from previous bouts of exercise, the systems could suggest safer movement patterns or with real-time built in alerts, smart clothing could even help to reduce injury during participation. Smart clothing is a necessary and welcomed improvement to activity monitoring since these once challenging factors resulted in extreme sports being previously neglected in research. As smart clothing becomes increasingly ubiquitous, a review of the current literature is essential to better understand the variety of materials, sensors and combinations currently available as well as their most beneficial uses. The aim of this review is to summarize the most recent research of smart clothing and identify its potential applications so that athletes, trainers, researchers, and practitioners have a better understanding of its functional application in extreme sports.

METHODS

This systematic review was conducted according to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines (Harris, 2014).

Search strategy

A comprehensive electronic literature search was conducted in April 2019 on the following electronic databases (2003 or more recent): Web of Science, Science Direct, PubMed, IEEE and Scopus database. Custom queries using keywords and Boolean logic with AND/OR were entered in the search engines with the following terms: ("Smart" AND "clothing") OR ("clothing" AND "sports" OR "sport"). The search included only full length original articles on human subjects and written in English.

Inclusion Criteria

The adopted inclusion and exclusion criteria were defined according to the (P; Patients, I; Intervention, C; Comparison, O; Outcomes) PICO components reported in **table I.** All the 24 of the included studies were evaluated according to the Newcastle-Ottawa Scale (NOS) by an engineer specialized in the field of smart clothing.

Table I. Eligibility criteria.

Selection Criteria	Inclusion criteria	Exclusion Criteria
Population	Humans	Not humans
Intervention	Smart clothing for monitoring sport	Wearable Device
Control	N/A	N/A
Outcome	N/A	N/A
Design	Meta-analysis, RCT, cohort studies, case control studies	N/A
Language	English	Not written in English
Other	Smart Textile for monitoring sport	Non-textile smart materials(1) not sport related papers (2)

RESULTS

Literature search results

A total of 837 records were identified after removing 58 duplicates. Title and abstract screening eliminated 786 papers, resulting in 51 eligible papers. Inclusion criteria then led to the exclusion of 27 papers resulting in 24 documents. The primary reasons for exclusion were the lack of compliance with the eligibility criteria (Tab.1). The selection process is represented by the flowchart in **figure 1.**

DISCUSSION

Study design, study object, general population, methods and results assessed according to NOS are reported in **table II**. After the first publication in 2003, there was an increase of pertinent publications over time. There were five from 2004-2008, seven from 2009-2013, and 11 from 2014-2018. Most of the studies where from Europe (72%; n=17), followed by Asia (12%; n=3), America (8%; n=2) and Oceania(8%; n=2). The countries with the most publications were: UK (23%; n=6), Italy (16%; n=4) and Finland (12%; n=3). The majority of these studies were overviews (29%; n=7) of textile, followed by overviews of requirement for designing smart clothing, overviews of the current status and future changes, products or prototypes, and data transfer. In total, we examined the data relative to 18 intelligent systems (See **table III**), some including more parts and accounting for a total of 22 types of clothing, including 13 shirts or vests, three pants, two socks, two bras and two gloves. As reported in table 3, twelve of the devices were able to capture the heart rate, three electromyography, and five the respiratory rate. Two systems incorporate GPS, three step counting, and five measure the energy expenditure. Three systems

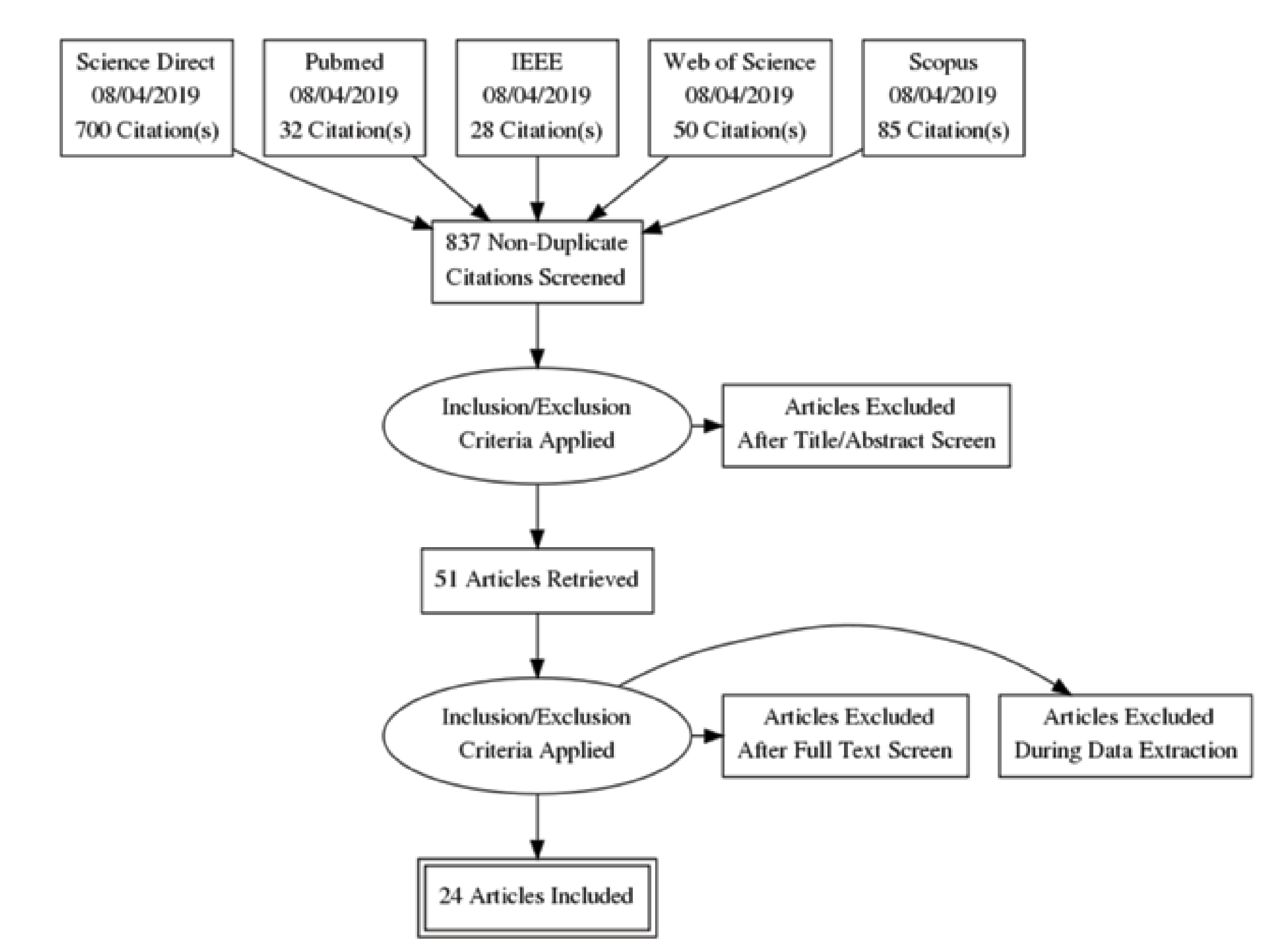

Figure 1. Flowchart of the review process.

Table II. NOS.

Studies	Selection	Comparability	Stars
Andreoni, Standoli, Perego, 2016	*	*	2
Axisa, Dittmar, Delhomme, 2003	**	*	3
Balmain et al., 2018	**	**	4
Bryson, 2009	*	*	2
Chan et al., 2012	**	**	4
Chittenden, 2017	**	*	3
Cho and Lee, 2015	***	**	5
Di Renzo et al., 2010	***	*	4
Dabby et al., 2017	**	*	3
Ghahremani Honarvar, M., & Latifi, M., 2016	*	**	3
Helmer, 2008	**	*	3
Lam Po Tang, 2015	**	**	4
Manshahia, 2016	*	*	2
Mečņika et al., 2014	*	**	3
Meinander, 2005	*	*	2
McCann, 2009	*	*	2
Mondal, 2008	*	*	2
Perego, Moltani, Andreoni, 2012	**	*	3
Rantanen, Marko, 2005	**	*	3
Rossi, 2018	*	*	2
Tyler, 2013	**	*	3
Uotila, M., Mattila, H., & Hänninen, O., 2006	*	*	2
Van Langenhove, L., 2013	**	*	3
Woods, 2008	**	*	3

Table III. Smart clothing products in sports.

Reference	Smart Product	Shirt/Vest	Pants	Socks	Bra	Glove	HR	EMG	Resp	Steps	GPS	Cal.	Posture	Activity	Temp.
Di Rienzo et al., 2010	MagIC	x					x		x						
Chan et al., 2010	Moticon SkiGo												x		
Balmain et al., 2018	Smart Vest	x					x								x
Tyler et al., 2013	Smart Socks			x						x					
Alisa et at., 2003	NuMetrex	x			x		x					x			
Rossi, 2018	MARSIAN	x				x									x
Rossi, 2018	VivoMetrics	x					x				x		x	x	x
Lam Po Tang, 2015	Oxstren					x	x		x			x		x	x
Lam Po Tang, 2015	SensVest	x					x							x	
Lam Po Tang, 2015	Athos	x	x				x	x	x						
Lam Po Tang, 2015	Sensoria			x			x			x		x		x	
Lam Po Tang, 2015	Hexoskin	x							x	x		x		x	
Lam Po Tang, 2015	Mbody		x					x					x		
Lam Po Tang, 2015	OM	x					x		x					x	
Lam Po Tang, 2015	Smartlife	x			x		x				x	x			
Lam Po Tang, 2015	AiQ, BioMan	x					x	x							
Chittenden, 2017	Heddok	x	x											x	
Perego, et al., 2012	Mart T shirt	x					x								
	TOTAL	13	3	2	2	2	12	3	5	3	2	5	3	7	4

measure the posture, seven identify the activity and four measure the body temperature.

Human System Interaction and Human-Centred Design in Smart Clothing in Sport

Smart clothing or "intelligent textile" represents a new class of wearable textile design systems with interactive technologies. Smart garments used in extreme sports should be specifically designed and built for the sport or missions they want to monitor. For example, some parts of the clothing, such as the electronic modules, can interfere with the sport equipment, including backpacks or specific harnesses; in these cases, special pockets or housings must be added (Di Rienzo, 2010). Special consideration must be given to the materials. Since many of these sports are practiced in particular climatic conditions and sometimes directly in contact with water, it is essential that the garment could contribute to thermal comfort of the subject. As a matter of fact, wet garments can be dangerous at low temperatures, while in warm humid climate conditions perspiration is crucial. Therefore, in extreme environmental conditions, synthetic materials such as neoprene or polypropylene may be preferred to cotton (Di Rienzo, 2010). Finally, the design must be optimized in order to ensure appropriate freedom of movement, and specific inserts of elastic fabric can be added in those areas that require maximum adherence to the body or freedom of movement. The human system interaction can be active (sensoric, adaptive, self-healing) or passive (e.g. barrier against wind, rain, or cold). Rantanen and Hännikäinen (2005) suggested a conceptual model that describes the architecture and the human system interaction of a smart clothing, **figure 2**.

According to this model, the inner clothing maintains the interface between the human and the textile. This layer can be connected with an outer layer with an insulation purpose. According to Andreoni et al. (2016) both layers can be served by user interfaces, such as buttons, fixing support and switches, or connectors providing input to the garments. Communication affects the smart clothing internally (data transfer between the separate components), externally (data transfer between smart clothes and external network), and spatially (data exchanges place between internal and external). Bryson (2009) addressed the relationship between design and the anatomical features, physiology and psychology, thus highlighting the role of human-centered design (**figure 3**).

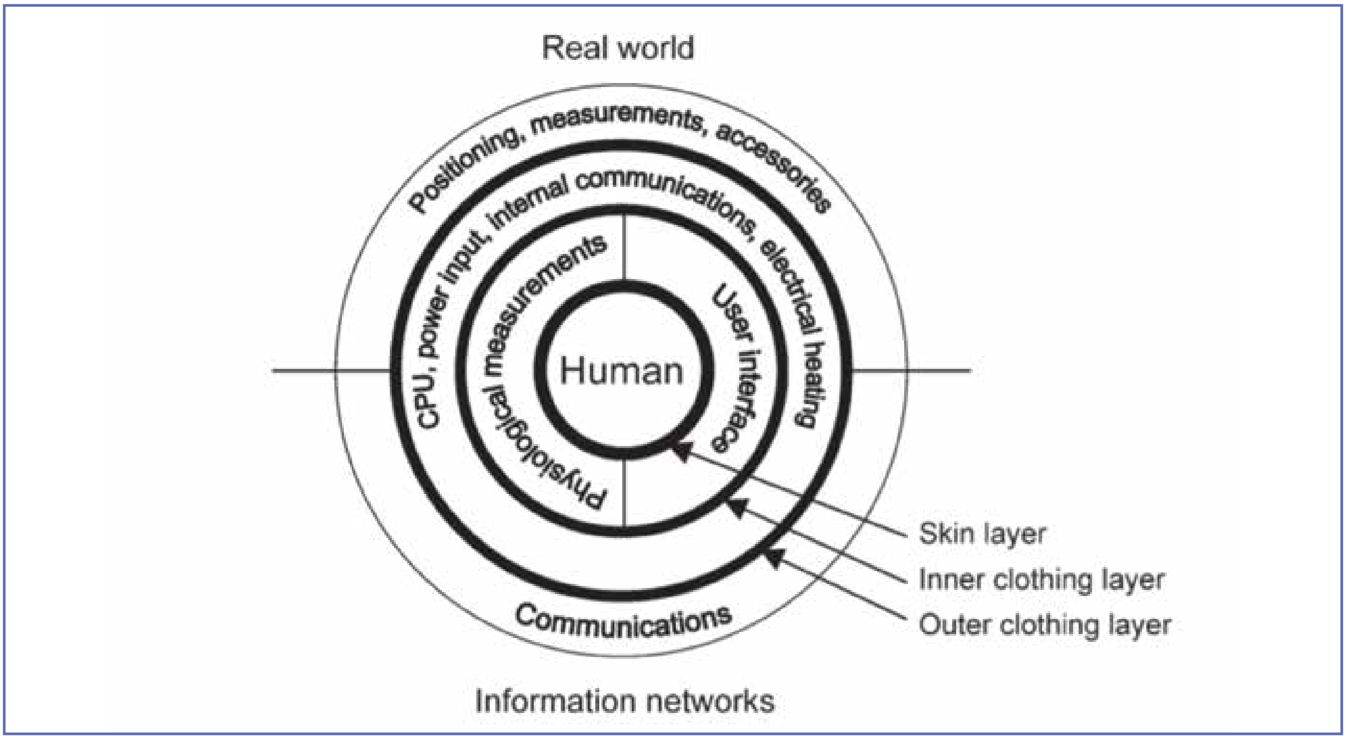

Figure 2. Concept model of smart clothing (Rantanen and Hännikäinen, 2005).

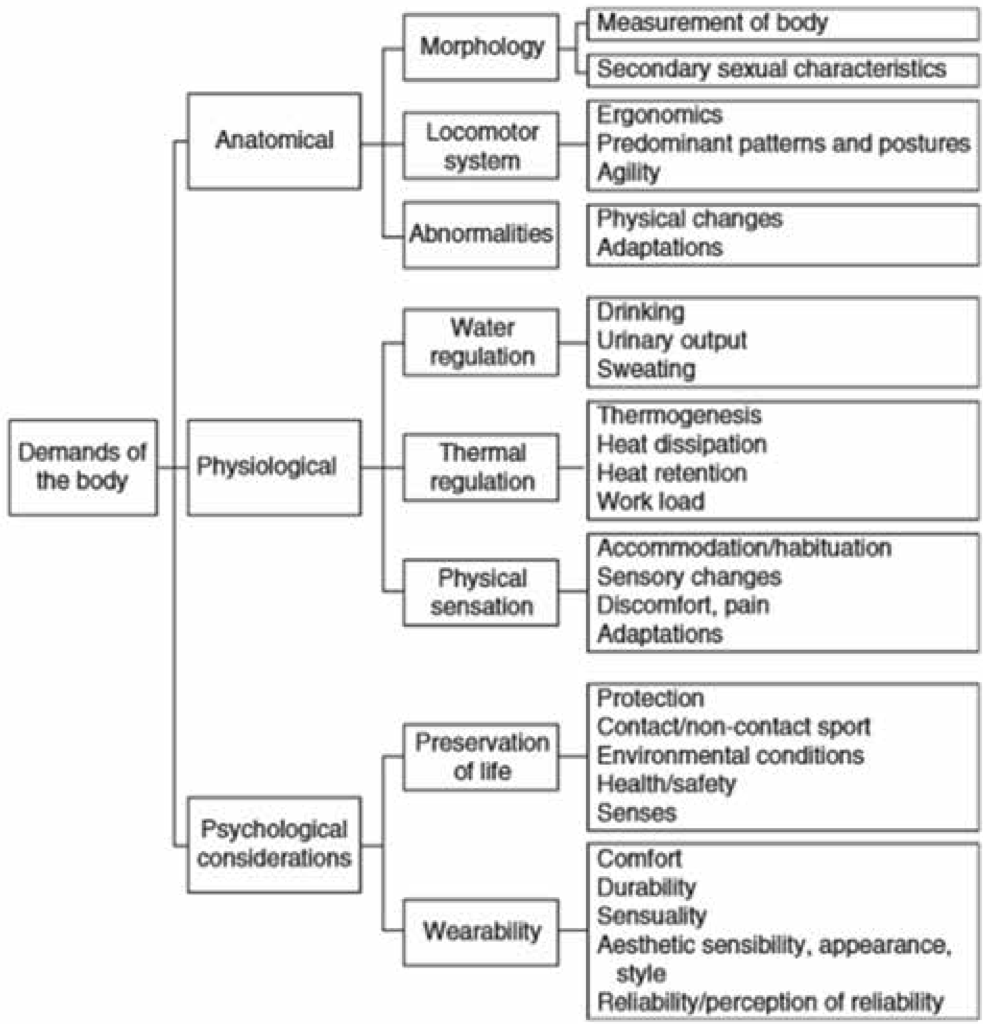

Figure 3. Schematic design of smart clothing design based on the demands of the body according to Bryson (2009).

McCann 2009, defined the garment design process for smart clothing using a different process. This process starts with the identification of the user and the user's needs by comparing the commercial realities. This step is followed by the 2D development of the garment together with the textile selection. The following step involves the initial 3D development with the measurement/ body sizing both with traditional and digital methods. In functional garment for sport, the joining technology uses innovative systems such as seamless, whole garment and knit & wear. Moreover, garment bonding, and stitch-free laser welding are used where it is necessary to develop high performance sportswear. Alongside the smart textile technology and the design of technology interface are developed.

Smart Materials

Smart materials in sportswear include fibers, yarn, fabric, coatings, finishes and membranes.

As explained by Ghahremani, Honarvar, and Latifi (2016), conductive fibers or Electronic Textile (E-textile) are fibers that conduct electricity through the smart clothing. They consist of natural (ferrous alloys, nickel, stainless steel, titanium, aluminum, copper) or threaded conductive fibers (conductive metal or carbon powders). As depicted in **figure 4**, conductive fibers can be merged with insulating fiber to create different structures.

When more than one fiber is interlocked, it is called yarn. The yarn can be made by conductive polymers or metallic fibers (natural, synthetic or created by wrapping). In turn,

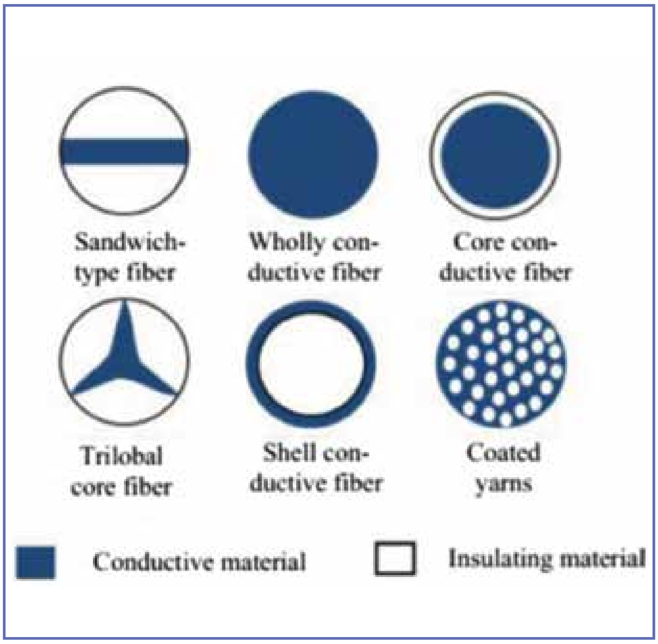

Figure 4. Different structures combining conductive (blue) and insulative (white) fibers to produce conductive textiles (Ghahremani, Honarvar, and Latifi, 2016).

the fibers could be used for embroidery, knitting and weaving, creating a garment. Conductive inks are inks with a metal precursor such as carbon, copper, silver, nickel and gold. Optical fibers can be integrated in the textile in order to transmit data signals, light or detect information related to stress and strain inside the fabric. Smart coatings such as phase change materials, moisture-responsive shape memory polymer, and conductive coatings are materials that can sense and respond to external stimuli and have recently been used in the production of sportswear. Smart coating with nano-particles can enhance the textiles with properties such as anti-bacterial, water-repellence, UV-protection and self-cleaning, while still maintaining breath-ability and tactile properties of the textile. Smart coatings for protection are smart membrane. Fluoroethylene membrane (PFTE) and Gore-Tex are created to protect the fabrics from water, while polyurethane membrane, like Porelle Dry, Dorminaz NX are used for waterproof breathable fabric.

Smart Coatings for performance enhancement

Smart coatings can be used to reduce drag in sports such as cycling, sprinting, and swimming. For example, biometric Swimsuit Fastskin® is a fabric inspired by the skin of a shark which has dimples on its surface which greatly reduce the drag through water.

Smart Coatings to enhance comfort

Phase change materials (PCM) are materials that responds to any external stimuli passing from one state to another, like solid to liquid, or vice versa. PCM microcapsule can change state from solid to liquid with temperature donating a cooling effect (when temperature raised to 29º C, they became liquid) or heating effect (when the temperature goes below 27º C, they solidify). PCM acts also as a barrier for the human body by creating thermoregulatory effects around the body by keeping the surrounding temperature constant either through heat emission or absorption. An example is the Outlast® technology originally developed by NASA for the temperature variation in space. The PCM microcapsule can be incorporated into fabrics and fibers giving the garment the capacity to absorb and release heat.

Shape Memory materials

In shape memory materials (SPM), moisture acts as external stimuli. An example is Nike sphere react t-shirt made by bilateral structure. An outer layer with U-shape (non-swelling and non-hygroscopic) and an inner layer (hygroscopic in nature). In this case, during an activity, the moisture acts as an external stimuli provoking the U shaped windows to curl back, while the opening increase the air permeability and cool down the body, allowing faster drying.

Physiological and Performance Monitoring

Bio signals are usually collected on the skin surface through sensors. The basic signals and the main parameters that can be measured by a smart textile are related to cardiac function such as hear activity (ECG), muscle activation (EMG), and respiratory rate. These signals are measured by electrodes which can be embedded into the cloth becoming textrodes. These sensors have the advantage of not requiring electro-conductive gel on the electrodes, also making them more ecologically friendly. The skin moisture and perspiration acts as electrolyte layer between textile and skin. This can be seen as stainless steel yarns that are used to embroider electrodes. These electrodes present high conductivity, but low elasticity and weight. The silver-coated polymer foams have the advantage of being antibacterial, but as metal-coated sputtered fabric, present poor washability. Signal strength is affected by the choice of the material and its integration into the cloth. In fact, ECG sensors, in particular textrodes, must be placed in an optimal position into the garment to prevent movement related artefacts. Dabby et al. (2017) described the process to building the garment with ECG textrodes embedded. While, Cho and Lee (2015) studied 56 electrode positions determining a smart vest grid with 6 cm intervals in front and back of the bodies. Ten subjects were monitored in the 56 different positions. A participant stayed still in upright posture wearing the smart vest. Fifty-six task sets of the experimental motion were repeated three times with ten second interval (Cho and Lee 2015). The optimal position (determined as the "maximal impulse") was shown to be in the 5d and the 2d positions, which correspond to the inferior, lateral side of the muscle pectoralis major. Together with cardiac data, smart clothing in sport can be used for monitoring breathing data, muscle activity, temperature, humidity or sweat data. In particular, textile structures that contains electro-conductive material can be used as strain gage for measuring respiration rate. Stainless yarns, for example, can be knit into a Lycra to provide stretch constituting a textile sensor for measuring respiration. Or, conductive polymer polypyrrole can be associated with Lycra constituting a chest-band integrated in a shirt for measuring the breathing rate (Lam Po Tang 2015). As an alternative, De Rossi (2018) coated yarns and fabrics with carbon loaded rubber to create a piezoresistive fabric strips positioned at the thorax and abdominal level. Andreoni et al., 2016 presented a smart shirt for monitoring respiration through textile strain gauges at thorax and at abdominal level. Di Renzo et al.2010 and Perego et al. 2015 presented one single lead ECG that is obtained by two knitted electrodes integrated in a vest and shirt at thorax level. In particular, the wearable system developed by Perego et al (2015) was used to capture the ECG signal along with three axial acceleration during a skyrunning race. Di Renzo et al.2010, presented the MagIc that below the textrodes for the ECG integrates piezoresistive plethysmograph that detect change in the thorax.

Textile sensors for kinematic monitoring in Sport

Kinematic analysis can be done through the use of body-worn accelerometers attached to the cloth by two snaps attached on the chest of a smart t-shirt to monitor the activity, balance and gait. Multiple accelerometers or inertial systems can be integrated in a suit constituting a motion capture system. Strain sensors integrated into a cloth can provide the characteristic of the movement or posture. A GPS or antenna can provide information such as speed and location.

Smart clothing products

Table 3 is a summary of the smart clothing products in sports which were found during this review, as well as their functionality. Athos smart garments (pants) are smart training tools used to optimize fitness level by monitoring the maximum voluntary isometric contraction (MVIC), rather than the typical neural EMG. Myotec is another smart product for measuring muscle activity that can be used for training. Also related to training, Sensoria launched a line of Smart Socks, Bra and Shirt which are connected via an app for virtual coaching during running and walking. Sensoria smart socks monitor cadence, pace, distance, foot loading and foot contacts. HR monitoring is possible using the bra or the shirt. By integrating the garments with the socks, the acquired information is used in a virtual coaching platform. HR monitoring is also possible by using the smart apparel BioMan+ (shirt, bra, vest) from AIQ or OMsignal (bra, shirt). Along with these options is a slightly different garment. Smart glove by Oxstrean can be also used for monitoring HR, respiration and hydration level during exercise, but the most complete smart garment that appears in this review is Astroskin from Hexoskin. This smart vest, born from the Canadian Space Agency with the aim to monitoring astronaut's vital signs, is now also available on the market. The Astroskin shirt measures blood pressure, pulse oximetry, 3-lead ECG, respiration, skin temperature, and activity sensors for 48 hours.

Possible applications of smart clothing in extreme sports

The use of smart clothing in extreme sports has, so far, been very limited. However, in extreme sports, these systems may be particularly useful, mainly because they allow monitoring the performance as well as physiological data in a non-intrusive way. Pressure sensors integrated in apparel can be adopted for measuring muscle activity, while strain sensors can be used for estimating muscle fatigue (EMG). These data are important not only for improving an athlete's performance, but also the quality of life by checking health status and preventing illnesses and injuries, including cardiovascular events (Di Rienzo, 2010). For example, the MagIC system was used to monitor physiological effects of altitude in ten climbers during their stay at 6000 and 6800 m (Everest South Advanced Camps 1 and 2). (Di Rienzo, 2010). Finally, smart clothing is an ideal solution for research in this field. They have been used for identifying possible countermeasures to altitude sickness (Di Rienzo, 2010). Smart clothing offers an ecological approach for monitoring physiological data monitoring of the performance of the athletes acting as safety mechanism in acting sport informing his team, if a problem arises.

CONCLUSIONS

This review identified and classified the main smart clothing that are used in sports. From this study, evidence emerged that Europe represents the most productive continent with the 72% followed by Asia with 12%. Smart shirts are the most commonly used garment for health monitoring parameters such as heart rate in sport activities, while other garments such as pants, glove, socks and bras have been explored. Extreme sports may be ideal scenarios for the smart garment employment, because most of them are practiced in remote and adverse environments, and they often involve acrobatic stunts. Smart clothing represents a safer solution to monitoring athletic performance both for medical and research purposes. Together with telemedicine, smart clothing can be used in adverse environments to enable data acquisition and provide critical information regarding injury prevention and training support without hampering athletic performance.

LIMITATIONS

The Newcastle-Ottawa Scale Quality Assessment Scale (NOS) was used to evaluate the quality of the studies selected in this review. However, this method presents difficulties in evaluating the scoring since the topic is multidisciplinary. Normally a score ≥7 is attributed to studies of high quality. In this review all the studies presented a score <7indicating low quality. Smart clothing is a new emerging innovative technology that need much more to be tested, explored and validated to satisfy the NOS scores.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests (32).

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