Sports helmets now and in the future

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ABSTRACT

The paper reports on a symposium on sports helmets and presents a synthesis of information and opinion from a range of presenters and disciplines. A review of the literature shows that helmets play an important role in head injury prevention and control. Helmets have been shown to be very efficacious and effective in a range of sports and in preventing specific head injury risks, especially moderate to severe head injury. The symposium emphasised the importance of helmet standards and the need for further development. There are calls for helmets that address the needs of competitive (elite) athletes separate to helmets for recreational athletes. Deficiencies in the evidence base for head injury risks and helmet efficacy and effectiveness were identified in some sports. Issues in designing helmets that are suitable to prevent severe head injuries and concussion were discussed and explained from biomechanical and engineering perspectives. The need to evaluate helmet performance in oblique impacts and incorporate this into standards was covered in a number of presentations. There are emerging opportunities with in-helmet technology to improve impact performance or to measure impact exposure. In-helmet technology as it matures may provide critical information on the severity of the impact, the location of the injured athlete, for example, snowboarder, and assist in the retrieval and immediate, as well as the long-term medical management of the athlete. It was identified that athletes, families and sports organisations can benefit from access to information on helmet performance. The importance of selecting the appropriate-sized helmet and ensuring that the helmet and visor were adjusted and restrained optimally was emphasised. The translation pathway from the science to new and better helmets is the development of appropriate helmet standards and the requirement for only helmets to be used that are certified to those standards.

INTRODUCTION

This paper presents a detailed summary of the symposium on sports helmets held at the 2011 International Olympic Committee World Conference on Prevention of Injury and Illness in Sport. This paper follows the symposium structure and the discussion is a synthesis of the issues considered during the panel discussion that concluded the symposium. The symposium considered all levels of sport in the formal presentations and the discussion, for example, competitive (elite) and recreational athletes. One of the aims of the symposium was to identify and highlight helmet topics that required research, policy and/or practical attention. A summary of these topics is also provided.

Helmets or padded headgear are used extensively in a wide range of sports where there are head impact hazards and injury risks. Helmets have been found to be very successful in some applications, for example, reducing moderate to severe head injuries, and less so in others (table 1). Some reasons for this include research ethics considerations, research design, insufficient funding, immature technology, helmet design and performance versus the sports requirements, standards and deficiencies in biomechanical knowledge and tools. In the past decade, there has been a much greater focus on resolving these issues, with some success, and many new opportunities for preventing head and brain injury have been developed. Much of this is presented below. This paper summarises head and brain injury risk, helmet performance and target areas for helmet development.

EVIDENCE BASE FOR SPORTS HELMETS

Table 1 summarises head injury risks and the evidence base for helmet function, efficacy and effectiveness in a selection of sports. Powered vehicle sports, such as motorcycle racing and motocross, have not been considered. The results show that there are two primary head injury risks that may be modifiable with helmets, namely concussion and severe head injury.

Concussion is an injury risk because of its frequency as well as the short- and long-term neurocognitive consequences on brain health and function. Severe head injury is a risk because of the health consequences to the individual and the economic effects for society. In some sports, such as US football, soccer, rugby and Australian football, concussion is the main brain injury risk. In other sports, there are severe head injury risks, for example, equestrian and pedal cycling, in addition to concussion. In projectile sports, such as cricket, baseball, women's lacrosse and ice hockey, oro-facial injury is of significant concern and has led to protective visors being worn attached to helmets.

The incidence and severity of head injury, including brain injury, varies greatly between sports. Depending on the sport, head injury accounts for up to 50% of injuries by body region. Concussion accounts for up to about 15% of all sports injuries by nature of injury. Helmets have been shown to be beneficial in reducing moderate to severe head injuries in alpine sports and bicycling. In equestrian sports, it is challenging to measure helmet effectiveness or efficacy, because all amateur and professional jockeys wear a helmet. It is presumed from a historical perspective that equestrian helmets are effective, but that they are not currently optimised

Table 1 Summary of head injury risks, helmet benefits and areas for future injury reduction

	Injury risk			Helmet		Target future injury reduction
	All head injuries—as proportion of all injuries and/or rate	**Concussion—as proportion of all injuries and/or rate**	**Severe TBI**	**Benefit**	**Evidence strength**	
Football (soccer)[23–33 36 49–53]	4–20% all levels	3% all levels UEFA: 0.06/1000 h Boys high school: 0.59 per 1000 A–E (comp) College male 1.08 per 1000 A–E (comp)	Minimal risk	63% reduction concussion	One population study, limited laboratory studies	Goal keepers
Rugby[37 54–56]	14–25% 8.1/1000 h (youth). 6.6/1000 h (pro)	5–15% 6.9/1000 h (youth) 4.1/1000 h (pro)	Minimal risk	None. Positive trend with novel design	Multiple well-designed laborarory and population studies	Concussion
American Football[51 53 57]	H/F 12% (high school) H/F 8% NCAA	6.1% Boys high school: 1.55 per 1000 A–E (comp) College male 3.02 per 1000 A–E (comp)	Medium risk≈7 catastrophic head injuries per annum US College/High School	74% decrease in fatalities and 84% reduction in serious head injury since 1976.	Multiple well-designed laboratory and population studies	Concussion
Projectile Sports[48 51 53]	3–25% cricket 11% baseball	Baseball–Boys high school: 0.05 per 1000 athletic exp (overall) 0.0043/1000 hrs (elite) Cricket: 1.5/1000 h	Minimal risk	Not quantified	Laboratory studies, limited population studies	Facial injury in cricket
Equestrian[58–62]	19–48%	15% 0.1 to 4.2 per 1000 rides	High risk	Not quantified, but large	Laboratory studies, limited population studies	Severe and fatal head injury
Bicycle[39 63–65]	General: 54 H/F/N ED pres per 100 000 population (with helmet) Road race: 0.59 per 100 000 km (with helmet)	Not quantified	Medium risk	63–88% reduction HI	Multiple well-designed laboratory and population studies	Severe and fatal head injury and concussion
Alpine Sports[34 66–70]	15–30% (all levels) 2010 Winter Olympics—17%	9.6% skiers 14.7% snow boards (high school and college) 0.05/1000 h (elite) 2010 Winter Olympics—17 per 1000 competitors	High risk	15–60% reduction HI	Multiple well-designed laboratory and population studies	Severe head injury in competitive snow sports Concussion in all snow sports

NCAA, National Collegiate Athletic Association; TBI, traumatic brain injury.

to protect jockeys in horse racing. In Australian football and rugby, there is no evidence that padded headgear prevents head and brain injury. In a comprehensive review of historical and other sources, Biasca *et al* reported that the combination of increased helmet wearing and rigorous helmet standards had reduced the incidence of fatal and serious head injury in ice hockey, although concussion was a growing concern.[1]

It is important that future sports helmet developments consider the key performance drivers, such as a targeted and agreed reduction in head and brain injury risk. For example, if a sports organisation identified that they wished to reduce head injury incidence or severe brain injury incidence by 25%, this would facilitate an informed debate among all stakeholders about the most suitable approach, including whether this could be achieved through helmet design and how. The costs and benefits of strategic developments in sports injury prevention could then be evaluated and provide clarity to sports helmet manufacturers and developers, standard organisations and athletes.

BIOMECHANICS OF SPORTS HEAD INJURY AND HELMET DESIGN

Little has changed in helmet safety design during the past 30 years. The typical helmet has a comfort liner, an impact energy attenuating liner, a restraint system and a shell (figure 1). Not all helmets have shells and these are referred to in the paper as padded headgear. Motorcycle and equestrian accidents' statistics using data from Germany, Canada and Finland found the most common impact situation to be an oblique impact with an average angle to the ground of 30°.[2–4] A pure radial impact will cause linear acceleration of the head while a pure tangential impact around the head's centre of gravity will cause rotational acceleration of the head (figure 2). In reality, pure radial impacts are very rare and would mainly cause skull fractures and injuries secondary to those. It is more likely that an oblique impact will occur that gives rise to linear and rotational head acceleration (figure 2). The human brain is sensitive to rotational motion.[5–7] Current helmets are, through energy-absorbing liners, optimised to reduce the linear acceleration of the head and related injuries, such as skull fractures.[8] A study by Mertz *et al* (1997) estimated a 5% risk of skull fractures for a peak acceleration of 180 gravities (*g*) and a 40% risk of fractures for 250 *g*.[9] Since rotational motion is not included in any current helmet testing standard, it is not known to what extent the current helmets reduce the rotational accelerations during a head impact.

The bulk modulus of brain tissue is roughly 10^5 times larger than the shear modulus.[10] Thus, the brain tissue can be considered as a fluid in the sense that its primary mode of deformation is shear. Therefore, rotational acceleration may be a better

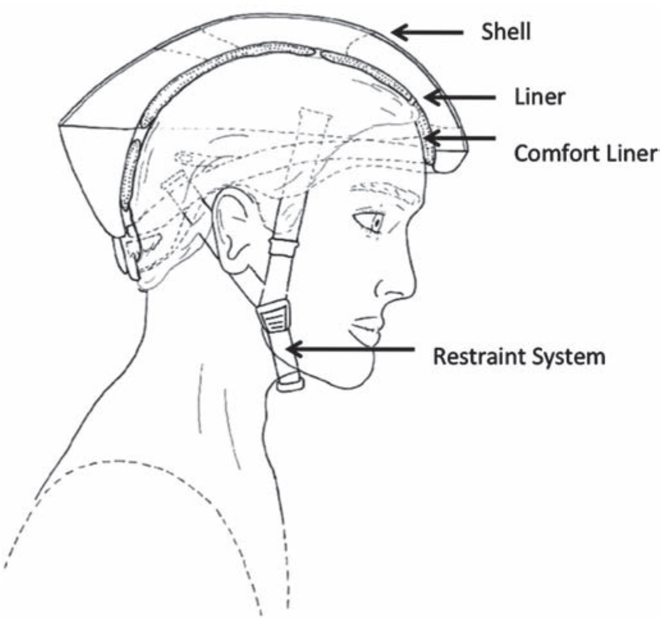

Figure 1 Schematic diagram of a typical helmet.

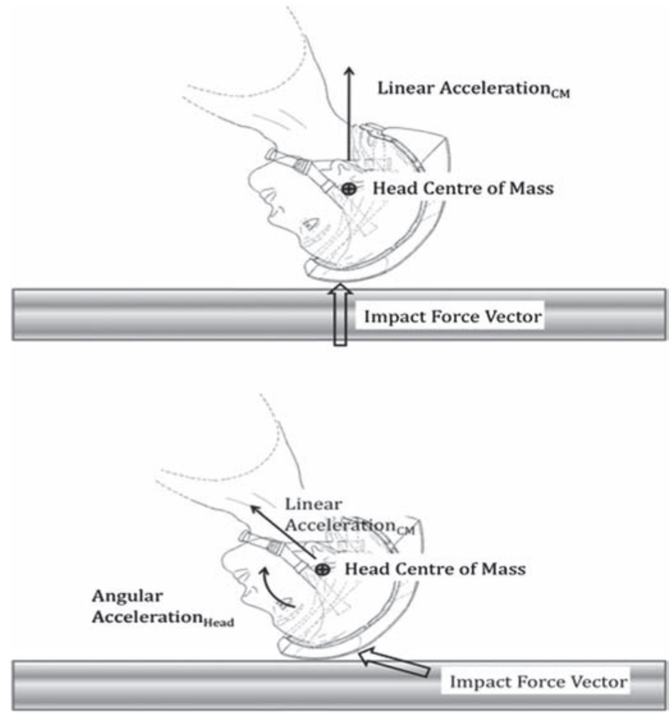

Figure 2 Schematic diagram of head impact. Radial impact (top) with linear head acceleration outcome and oblique impact (lower) with linear and angular head acceleration outcome.

indicator of traumatic brain injury risk than linear acceleration; the most common severe injuries such as subdural haemorrhage and diffuse axonal injury are more easily caused by rotational head motion.[5 11] However, these occur when the head is subjected to a severe impact. A typical helmet can reduce the impact force and as a result also reduce the magnitude of the rotational loads applied to the brain. Similar considerations need to be given to the mechanisms of concussion and design of helmets to prevent concussion. No generally accepted thresholds exist for rotationally induced brain injuries, but the tolerance curves for diffuse axonal injury by Margulies and Thibault indicate benchmark thresholds of around 8 krad/s^2 and 70 rad/s.[12] These limits need to be reduced when adding the translational acceleration to the impact pulse.[7 13 14] It is also likely that the thresholds will need to be different for different impact directions or include the head kinematics for all degrees of freedom of the head.[7 15]

PERFORMANCE STANDARDS FOR SPORTS HELMETS

There is a range of standards that have been developed for sports helmets by different organisations (table 2). Sports governing bodies, for example, International Federation of Association Football (FIFA), have generally not developed standards. Because the importation and sale of helmets may not be restricted only to standards-certified helmets, it is possible to purchase sports helmets that may not be certified to any standard. Standards are 'published documents setting out specifications and procedures designed to ensure products, services and systems are safe, reliable and consistently perform the way they were intended to'.[16] With regard to sports helmet standards, the authors are seeking at least

- Helmet tested to realistic or priority impact conditions for intended use and desired injury prevention outcomes.
- A compliance and certification process including batch testing.
- A satisfactory and appropriate level of biofidelity and reliability in the test system.
- Helmet reduces impact loads to tolerable levels (may still result in injury).
- Helmet stays on head.
- Helmet does not interfere with vision (or comfort).
- Helmet design does not 'induce' head loads (eg, high friction surface or projections).

These performance characteristics are typically covered through specifications around the following design, construction and/or performance aspects: impact protection (extent and level of protection, impact test description and performance criteria, test energy (drop height), anvil, impactor, conditioning (wet, hot and cold); retention system strength; helmet stability; vision; and labelling. There are variations in the test requirements among helmet standards for the same sport (table 3). The extracts from the three ski helmet standards indicate that the Snell standard includes high-energy impact tests onto three different anvils in contrast to the European Standard (EN), which has a lower-energy impact onto a single anvil. ASTM F2040 includes impacts against three anvils but at impact energies slightly less than Snell 98. Because the acceleration pass criteria are similar, the differences indicate that a Snell-certified helmet will have a more severe impact than an EN-certified helmet which manages the impact to produce similar head acceleration. Because the acceleration pass criteria are similar, the differences indicate that a Snell certified helmet will in a more severe impact than an EN certified helmet manage the impact to produce a similar head acceleration.

With recognition of the differing demands and injury risks between recreational, subelite and elite athletes, there have also been limited attempts to develop standards offering a level of protection that at face value is more appropriate for high-risk sports. For example, two European standards have been produced for equestrian sports helmets: EN 14572 intended for horse racing and EN 1384, a general use standard. EN 1384 required the peak headform acceleration of the headform not to exceed 250 *g* in a 1.5-m drop test against a flat anvil. In comparison, EN 14572 required the peak headform acceleration not to exceed 250 *g*, or 150 *g* for longer than 5 ms,

Table 2 Sports helmet standards ('✓' indicates standard)

Organisation	American Football	Rugby	Ice Hockey	Football	Baseball	Cricket	Snow Sports	Cycling	Equestrian
NOCSAE	✓	×	✓	×	✓	×	×	×	×
ASTM	✓	×	×	✓	faceguard	×	✓	✓	✓
Snell	×	×	×	×	×	×	✓	✓	✓
AS/NZS	×	×	×	×	×	✓	×	✓	✓
CSA	×	×	✓	×	×	×	✓	✓	×
EN (incl. BSI, DIN NSAI)	×	×	✓	×	×	✓	✓	✓	✓
ISO	×	×	✓	×	×	×	×	×	×
FIFA/FIS/IIHF/IRB	×	✓ (IRB)	×	×	×	×	×	×	×

AS/NZS, Standards Australia/New Zealand Standards; BSI, none; CSA, Canadian Standards Association; DIN, Germany Industry Standards; FIFA, Federation International Football Associations; FIS, International Ski Federation; IIHF, International Ice Hockey Federation; IRB, International Rugby Board; ISO, International Standards Organisation; NOCSAE, National Operating Committee on Standards for Athletic Equipment; NSAI, National Standards Authority Ireland.

Table 3 Comparison of impact energy attenuation test requirements for helmets in alpine sports among three standards. All standards refer to ISO dimensioned or equivalent headforms

Standard	Drop height (m)	Peak head-form Accel. (g)	Anvil	Drop height (m)	Peak head-form Accel. (g)	Anvil	Drop height (m)	Peak head-form Accel. (g)	Anvil
Snell 98	2.4	<300	Flat	2.2	<300	Hemi	2.2	<300	edge
EN 1077: 2007	1.5	<250	Flat	–	–	–	–	–	–
ASTM F2040	2.0	<300	Flat	1.2	<300	Hemi	1.0	<300	edge

in the following impact tests: 3-m drop onto a flat anvil, 2-m drop onto a hemispherical anvil, 2-m drop on to 'hazard' anvil and the peak headform acceleration not exceed 80 *g* in 1-m drop onto a flat anvil. The requirements are very different, reflecting the intent of servicing two distinct athlete cohorts and their injury prevention needs. There may be a value to the many stakeholders and interested parties in providing an on-line resource that summarises the current standard requirements, and a clear need to bring many elements, such as acceleration criteria, into alignment.

One limitation in the current helmet standards is the absence of a specific oblique impact test that measures or promotes designs that reduce head angular acceleration that arises in impacts. Although there are a number of test methods, the only method included in a standard at present is in UN/ECE 22 for motorcycle helmets.[17–19] The UN/ECE 22 test is, however, principally a test of the helmet's surface characteristics. For an oblique helmet impact test to be adopted, it will need to satisfy a range of performance criteria, including biofidelity of the head (size, shape, mass, inertia, helmet fit and restraint fit), repeatability, robustness, reliability and validity (use of appropriate injury criteria considering combinations of angular and linear kinematics, impact force, direction and location). These are complex and challenging issues.

A MANUFACTURER'S PERSPECTIVE ON SPORTS HELMET DEVELOPMENT

Manufacturers rely on scientific data, standards, market research, input from sports organisations and individuals in the development of helmets. They also rely on their inhouse design and engineering expertise. Helmet manufacturers and developers support the need for relevant helmet standards. From their perspective, standards provide the benchmarks for helmet performance, provide a fair playing field and access to markets. There is recognition of the differing requirements of competitive (elite) and recreational athletes, children and adults and a desire to supply products to those markets. However, the development costs for new helmets are considerable and these need to be factored into the thoughts of sporting organisations, standards committees and athletes, when there are calls for 'better' helmets. One section of the competitive sports helmet market where there has been progress is in motor sports, where helmets have been designed to protect athletes under extreme impact conditions. New shell and liner materials with properties optimised to minimise head and brain loads in radial, tangential and oblique impacts are always under consideration. Of these, some will emerge within new products.

ENHANCING HELMET FUNCTION AND NEW TECHNOLOGIES

Sports helmets do an excellent job at preventing traumatic head injuries that they were designed to protect against. However, as research on concussions and repetitive brain trauma advances rapidly, there is a demand for helmet technology to provide increased protection against these injuries as well. By attenuating impact energy, current helmets do reduce the forces acting on the head that might lead to these less severe brain injuries, but helmets alone may not be able to prevent rotational motion of the head that is thought to be linked to the stretching of axons in the brain linked to concussion. Efforts to use helmet technology in concussion prevention must not reduce their current protective capability against focal injury, nor add so much padding or weight as to make participation in the sport difficult.

Potential technology solutions for the prevention of brain injury should rely on research identifying the mechanism of sports-related brain trauma. Both single impact and repetitive impacts should be considered. The use of non-linear anisotropic padding materials which react differently to attenuate varied energy input, helmet geometries and construction to reduce rotational acceleration of the head following impact, and alternative attachment mechanisms to improve helmet fit and also to more efficiently manage energy are all design options that have or are being employed in new helmet designs. Sports-specific or even position-specific helmets address differences among and within sports and consider different hazards that might be encountered and likely head impact energies and directions. Single impact versus multiple impact helmets and

Figure 3 Helmet examples. Bicycle (top left), equestrian (bottom left) padded headgear (top right) and American football (bottom right).

their construction using inexpensive, lightweight materials such as expanded polystyrene and expanded polypropylene highlight these approaches. Novel technologies and materials used must also be cost-effective when mass production is required.

As new helmet technologies emerge with the intent of also addressing concussion prevention, laboratory testing and standards development for these helmets should be based on realistic loading conditions for that sport. Technology to monitor head impact exposure on the playing field, including head impact frequency, magnitude and direction (impact location), is used together with clinical diagnosis of concussion injury to develop risk curves for sustaining concussion based on variables including head linear acceleration, rotational acceleration, impact duration and impact location.[20–22] These data can be used to develop standard test methodologies and to inform helmet technology developments. On-field monitoring technologies should measure head motion rather than just helmet motion during impacts to correlate better with injury mechanisms.

Advances in helmet technology alone may not and are not likely to eliminate concussions in sport. Opportunities to reduce the incidence and severity of concussions in sport will emerge from the coupling of (a) appropriate education and rules (enhancement and enforcement) to minimise repetitive head impacts in sports and (b) novel helmet materials, geometries and designs based on emerging scientific data that elucidate the mechanisms of sports-related concussion.

SPORTS-SPECIFIC ISSUES

Equestrian helmets

The wearing of helmets is mandated in most equestrian sports and, in many instances, regional standards are also specified in the regulations (ASTM F1163 in the USA, EN 1384 in Europe and AS/NZ 3838 in Australasia). The introduction of helmets conforming to the draft BS:EN 1384 by the Jockey Club (GB) in 1992 appears to have had a direct impact on the number of fatalities due to head injuries in race riding. During the period 1985–1991, there were six jockey fatalities, five of which resulted from head injuries. From 1992 to 2010, there were a further six fatalities, none of which were due to head trauma. During both periods, the incidence of head trauma as a percentage of all career-ending injuries remained the same (20.8%–19.7%). There has been little change in helmet design in the past 15 years, and the issue of rotation is currently of particular interest (figure 3). Research into creating new equestrian helmet standards is overdue.

Headgear in football

Football is the only contact sport where the participants purposefully use their unprotected head to control and advance the ball; despite this, the risk of concussion and severe head injury is low (table 1). Controlled heading has not been shown to cause brain injury in laboratory studies in youth and adult players[23 24] and computerised neuropsychological testing revealed no evidence of neuropsychological impairment or brain cell damage

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due to heading exposure.[25–27] Head injuries are mainly caused from contact with other players[28–31] and the main mechanisms are elbow-to-head and head-to-head impacts.[28 29 32]

Laboratory studies testing headgear to reduce concussion and severe head injuries in head-to-head and ball-to-head situations are inconclusive. Headbands reduce linear acceleration very modestly; however, there is no protection against rotational acceleration of the brain.[33–35] Table 1 shows that one cross-sectional, non-randomised study using a symptom-based definition found that concussion frequency was significantly (2.7 times) higher among youth players who did not wear headgear compared with those who did.[36] However, this is the only, very weak, evidence that headgear protects the brain while playing football.

Headgear in rugby football

There is a definite risk of concussion in rugby football and a very low risk of moderate to severe head injury (table 1). To date, high-quality laboratory and randomised control studies of headgear have not shown that current designs are likely at a player population level or an individual player level to prevent concussion or head injury (figure 3). There may be other reasons why players wear headgear, for example, comfort and protection against very superficial injury. The Rugby Headgear Study and associated research identified a strong trend in protective performance for the 'modified headgear'.[37 38] This headgear was constructed from thicker and denser foam than a standard headgear and performed better in laboratory tests. In the randomised control trial, there was a non-significant reduction of 59% compared with no headgear in head injury (including concussion) leading to at least one missed games.[37] This result indicates the direction that rugby headgear might take to improve its performance and the importance of well-designed research in informing helmet development and assessing helmet efficacy.

Cycle helmets

Head injuries are the cause of death in 69%–93% of the fatalities in bicycle accidents. However, bicycle safety helmets have been shown to be effective in all epidemiological studies.[39] Current cycle helmet design provides good protection although certain political lobbying organisations have been claiming the opposite. Several myths regarding the protective properties of bicycle helmets have been explored by Mills and Gilchrist.[40] They found that the typical large vents seen in bicycle helmets do not cause excessive pressures on the skull. Furthermore, the long extensions at the front and rear of cycle helmets do not cause excessive rotation of the head. Even so, bicycle safety helmets can still be susceptible to improvement and especially the coverage at the side of the head can be improved.[41–43] This could easily be done by changing the test lines in future test standards. A further improvement in the rotational protection of bicycle helmets could be obtained by including an oblique helmet test and rotational head motion measurement in future test standards.[2 17–19] Nevertheless, the difference between not wearing a bicycle helmet and wearing a helmet in terms of accident outcome is much greater than wearing an optimal helmet (table 1). Thus, increasing helmet wearing rates to high levels (80% and above) through mandatory helmet laws and/or public safety campaigns is also a critical step to protect cyclists.

American football

The incidence of concussion in American football is relatively high compared with other sports, owing largely to the high number of head impacts experienced. College and high school age athletes are exposed to as many as 1400 head impacts during a single playing season, mostly of relatively low magnitude. While the short-term effects of these repetitive impacts on the measures of brain function quantified by cognitive testing or neuroimaging appear to be limited, less is known about the cumulative effect of head impacts over time; research on retired American football players has demonstrated a significant increase in the incidence of early onset dementia, potentially linked to repetitive head impacts.[44 45] Current efforts are aimed at better monitoring of head impact exposure at different age levels, correlation of head impact biomechanics with clinical sequelae surrounding concussion diagnosis, understanding the risk of brain injury due to rotational head motion following impact and the development of biofidelic test methods for reproducing head impacts in a laboratory.

Alpine sports

A recent systematic review based on 12 studies on recreational skiers/snowboarders concluded that skiers and snowboarders with a helmet were significantly less likely than those without a helmet to have a head injury (OR 0.65, 95% CI 0.55–0.79), and that there was no evidence of an increased risk of neck injury.[46] There are no data available from the competitive level.

According to the International Ski Federation (FIS) regulations, the use of crash helmets is compulsory for all events, conforming to standards such as CEE 1077 or US 2040, ASTM F2040, Snell S98 or RS 98, etc.[47] However, the question is whether these standards are appropriate, as they define performance requirements for use in recreational snow sports. It seems reasonable to assume that these requirements will be very different in World Cup skiing and snowboarding, where race speed may exceed 140 km/h down an icy course. Thus, there is a need to develop appropriate helmet standards for competitive skiers and snowboarders.

Projectile sports

As presented in table 1, there is a risk of head and facial injury in sports with projectiles, such as cricket, baseball and ice hockey. Over the past two decades, cricket helmet use has come to be the norm, despite there not being rigorous evaluation of their performance. Concerns have been expressed about the possibility of cricket balls breaching the helmet's face guard and causing eye and facial injuries. The standards for cricket helmets, unlike baseball, do not include impact tests for the helmet or the faceguard that are representative of projectile impacts.[48] Therefore, standards' development is one area of improvement. It has also been identified that correct helmet fit and adjustment of the restraint or faceguard are essential in ensuring adequate performance.

SUMMARY AND CONCLUSIONS

The following themes were reiterated in presentations and discussions during the symposium:

- Helmets play an important role in head injury prevention and control. Helmets have been shown to be very efficacious and effective in a range of sports and in preventing specific head injury risks, especially moderate to severe head injury.
- Helmet standards are important and there needs to be further development.
- Helmets for competitive (elite) athletes and separately for recreational athletes need to be designed and developed.

- Helmets for children, adults and older athletes, because of the differing human tolerance to impacts and impact profiles, need to be designed and developed.
- Deficiencies in the evidence base for head injury risks and helmet efficacy and effectiveness were identified in some sports.
- The difficulties in designing helmets that were suitable to prevent severe head injuries and concussion.
- The need to evaluate helmet performance in oblique impacts and incorporate this into standards.

The symposium identified the need for research in a number of areas and opportunities for the development of helmets with improved performance. There are many knowledge deficits that can be addressed through research, including improving the biomechanical understanding of the impacts that athletes are exposed to, and higher-quality studies of helmet efficacy and effectiveness across many sports. The emerging opportunities of in-helmet technology to improve impact performance or to measure impact exposure were discussed. In-helmet technology as it matures may provide critical information on the severity of the impact, the location of the injured athlete, for example, snowboarder, and assist in the retrieval and immediate, as well as the long-term, medical management of the athlete.

It was identified that athletes, families and sports organisations can benefit from access to information on helmet performance; an example of this is the STAR rating scheme for American football helmets.[21] Therefore, there is scope for independent consumer-oriented helmet testing and information dissemination. The importance of selecting the appropriate-sized helmet and ensuring that the helmet (and visor) was adjusted and restrained optimally was emphasised.

Finally, because of the high cost to the manufacturer to develop a new helmet, it is imperative that there is a broad stakeholder consensus on the need for new helmets. These costs may be in excess of €500 000 for a new product and involve retooling and other fixed production costs. The additional benefit of reaching and communicating a consensus is that products will be developed that meet strategic injury prevention objectives. The translation pathway from the science and the consensus to new and better helmets is the development of appropriate helmet standards and the requirement for only helmets to be used that are certified to those standards.

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