Modern Sports Helmets

Their History, Science, and Art



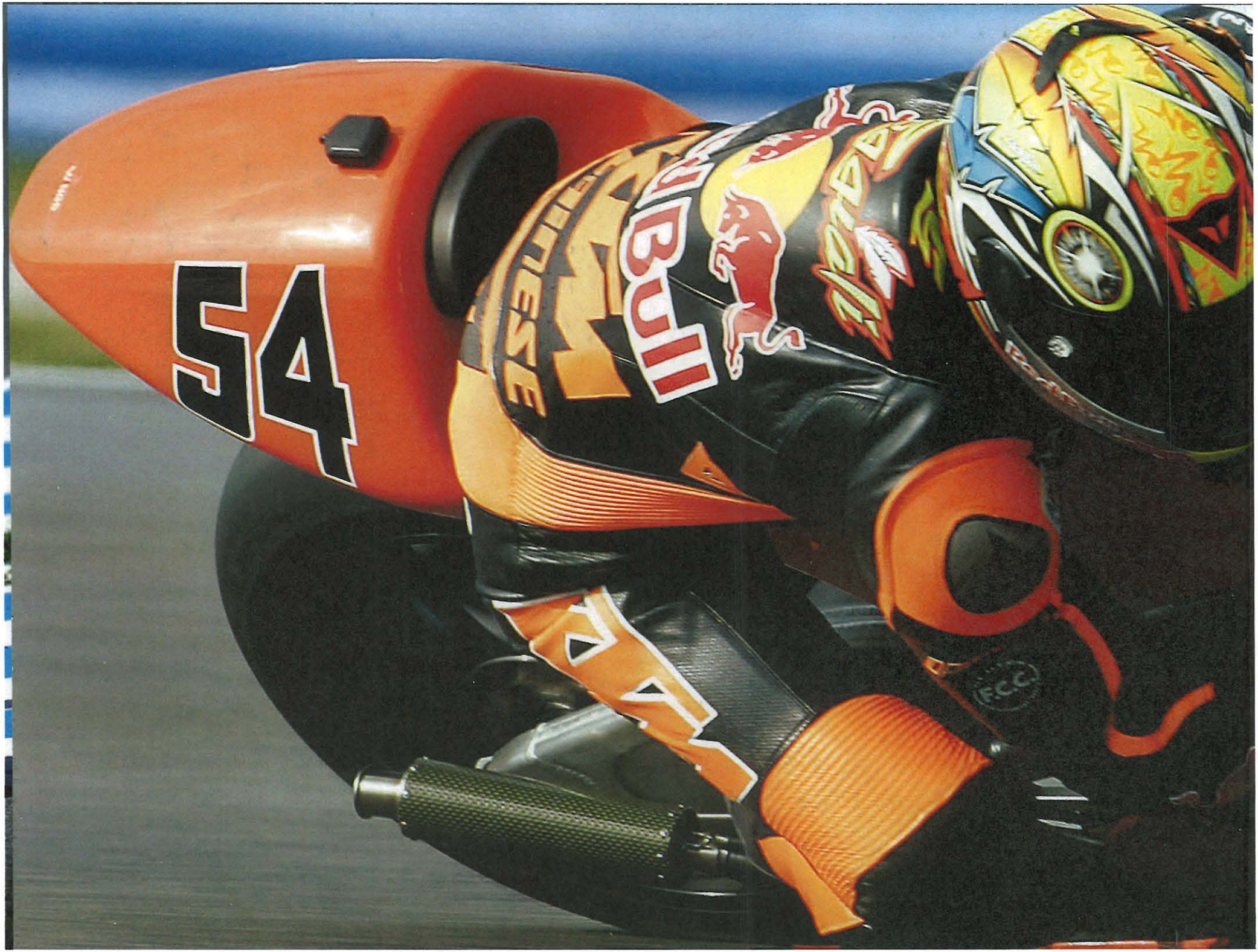




James A. Newman, Ph.D.

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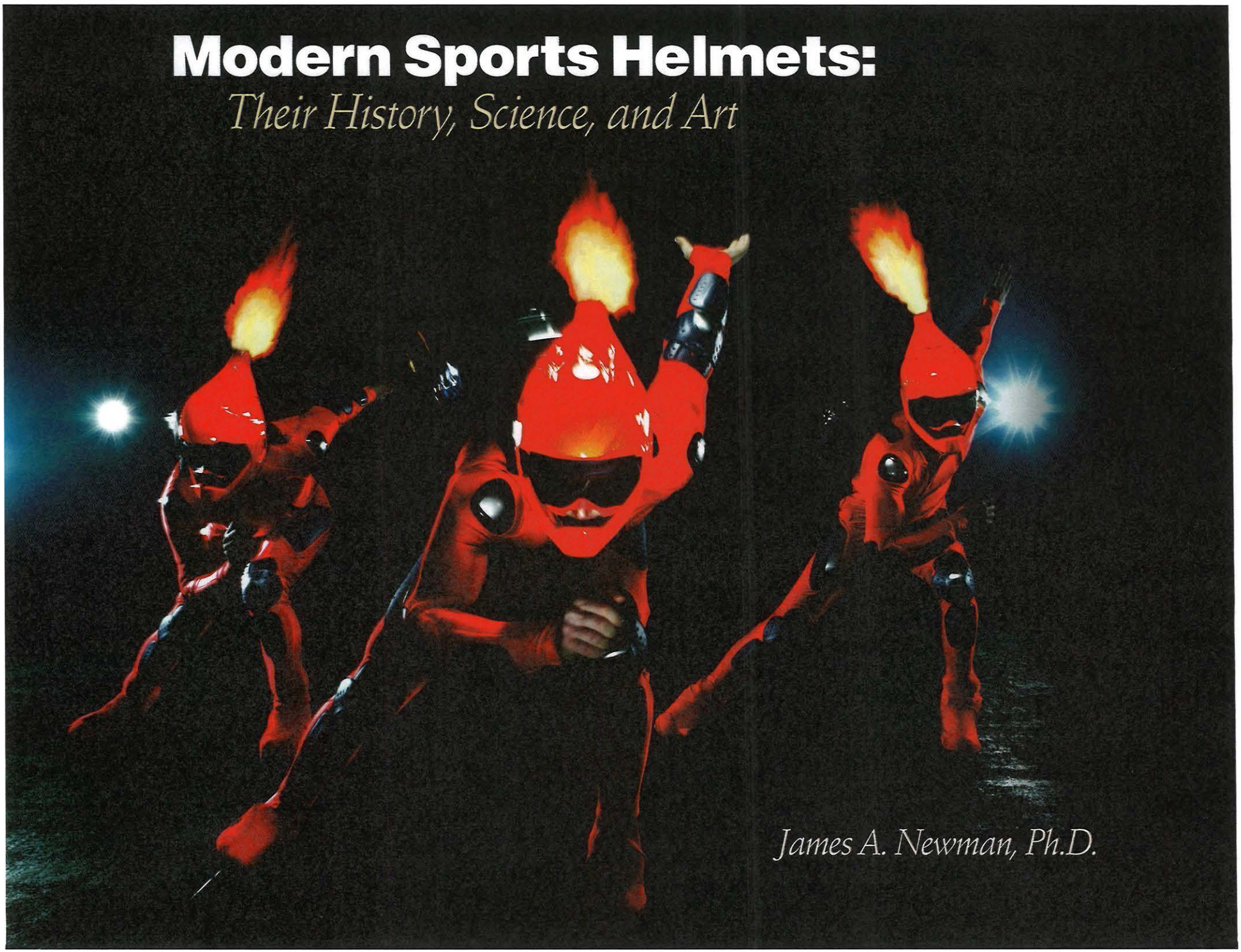
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Modern Sports Helmets:

Their History, Science, and Art



James A. Newman, Ph.D.

Dedication

In 1970, while a young Assistant Professor of Mechanical Engineering at the University of Ottawa, I was approached by a man who would change my life.

Professor Charles Cotton of the Department of Kinanthropology had received a research grant to develop a better hockey helmet. He needed some engineering help and asked if I'd be interested. Five years later he and I would incorporate a small research and development firm dealing with human protective systems, Biokinetics and Associates Ltd. Dr. Cotton would spend his entire career at the University, but that small firm was to become my life's work. Though I am no longer actively involved in the company, Biokinetics continues to do outstanding research in the protective systems field.

To *Chuck*, who was always there when I needed help, I owe the deepest gratitude.

For introducing me to the biomechanics of protective headgear, to him this book is dedicated.

(Dr. Cotton passed away in February 2007).

Other Schiffer Books on Related Subjects

The Motorcycle Helmet, The 1930s to 1990s. RinTanaka. ISBN: 0-7643-1639-7

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Covers and book designed by: Bruce Waters
Type set in Hallmarke Bold heading font/text font Zurich BT

ISBN: 978-0-7643-2718-6
Printed in China

Published by Schiffer Publishing Ltd.
4880 Lower Valley Road
Atglen, PA 19310
Phone: (610) 593-1777; Fax: (610) 593-2002
E-mail: Info@schifferbooks.com

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Acknowledgments

I could not have put this overview together without the help and input of many people.

I must first thank Nick Shewchenko, President of Biokinetics and Associates Ltd. of Ottawa, Canada. Many of the photographs herein were taken by Stephen Fenn at the facilities of Biokinetics where these helmets have been part of various development and testing programs over the years. I had been affiliated with Biokinetics for over 25 years and I am very grateful to all the staff that was so helpful in allowing Stephen and I to access this superb collection. I'm also very thankful to Stephen for his professionalism in his work with me.

No book about helmets would be close to complete without contributions from the pioneers at Bell Helmets. To Dean Fisher, Don L'Heureux, Terry Stern, and Vern Hancock go my deepest respect and gratitude.

There have been other important people in the helmet field who have also given their time and advice so freely and cheerfully. Ed Becker and Gib Brown of the Snell Memorial Foundation, David Halstead of Southern Impact Research Center, Dave Thom of Collision and Injury Dynamics, Terry Smith of Dynamic Research Inc., and Harry Hurt of the Head Protection Research Laboratory have all been a big help to me.

I also want to thank all those representatives of industry that have so willingly and freely provided images and data regarding their products. Included among them are:

Frank Plastino, International Riding Helmets.

Dennis Piper, Full 90.

Allison Chonko, Thad Ide, Ralph Infusino and Nelson Kraemer all of Riddell Co.

Sandra Gadoury of Louis Garneau Inc.

Carmella Livorski and Chris Bullock, Specialized Bicycles.

Eva Bermadinger and Thomas Schumacher of Scott.

Courtney Applewhite and David Higdon from Western Hardhat Int'l Inc.

Ted Kochowicz of Wilson Team Sports.

George Hong and Jason Oh, HJC

Vittorio Cafaggi of Dainese

Roger Weston of Arai Helmets

Marie Russell and John Dambrose, Impact Racing Products.

Marie-Claude Généreux and Jean-François Laperrière, Nike- Bauer Sports.

Eric Marquis, David Rudd, Craig Johnson, Mission-Itech Hockey.

Michelle Fortier and Evangelos Spyrou of The Hockey Company

Toby Henderson, VSI Products.

Kirk Chung, KBC Helmets.

Larry Maddux, Schutt Sports Mfg. Co.

Phyllis Howard and Gary Montgomery of Adams USA.

Hiro Mizushimi, Shoei Helmets.

Katherine Appuhn-Hodges and Kyle Kietzmann of Bell Auto Racing.

Debbie Bishop of Simpson Performance Products.

David Zampierin, Zamp Racing Corp.

Richard Timms, Troxel Corp.

Bob Hubbard, HANS Performance Products

To those manufacturers that chose not to participate and those with whom I was unable to make contact, I hope you will nevertheless find this book of interest.

Many other colleagues and friends helped make this happen, including Dru Malavasi, Dave Viano, and Jocelyn Pedder, Thom Parks and his son Ryan, a professional photographer who provided many of the historical images. Chris Withnall at Biokinetics, Marc Beusenberg and Jac Wismans of TNO in Holland, Nigel Mills from the University of Birmingham in UK, Pat Bishop from the University of Waterloo, Liying Zhang of Wayne State University, Tom Gennarelli, Medical College of Wisconsin, and Randy Swart of the Bicycle Helmet Safety Institute in Washington, have all been very helpful in one way or another. My dear wife Helen put up with me during this process and certainly without her help and forbearance, this would not have happened. Several friends reviewed draft copies along the way and have made suggestions and pointed out errors. And though I have strived to be as accurate as possible, there may still be some mistakes in here, for which I take full responsibly.

A fair number of the images here came from various photo collections or archives whose contributions I most gratefully acknowledge

Richard Radcliffe from the Isle of Man graciously provided photos of the great motorcycle racer Joey Dunlop.

Graham Watson was kind enough to let me use his photo of Lance Armstrong.

Mary Brace of Brace Photo supplied several shots of old time football players.

Morry Barmak from Collector Studio, J. P. Boutros of Autosport-Net, and Marie Gunn of JMJ Automobilia all provided images of replica and actual headgear worn by various famous racing drivers.

Kathy Weida and Dan and Evi Gurney of All American Racing most graciously provided background and photographs of Dan's original Bell Star helmet.

Kelly Hudak, Rick Menapace of Plummer Menapace Group, and Dan Mahoney, Motorcycle Hall of Fame member, gave me a collection of great motorcycle racer photos.

Michael Levitt, LAT Photography graciously and freely provided many outstanding photos of auto racing helmets and of various drivers

Paul-Henri Cahier, Cahier Archive, supplied great color action images of vintage and contemporary race car drivers at work.

Michael Varndell of the UK presented me with terrific images of old time car racers including those of Malcolm Campbell and John Cobb.

Chris Nazarenus, Artemis Images, freely provided superb images of Jackie Stewart and Dan Gurney

Craig Campbell of the Hockey Hall of Fame sent images of my hockey heroes.

Rob Jones, Canadian Cyclist Magazine, and Lori-Ann Muenzer, Canadian Olympic Gold Medal cyclist, arranged for me to secure great photos of cycling events.

Heidi Vahue and David Crystal took some great pictures of vintage equestrian helmets for me to use in the book.

Michael Woodhouse of the Canadian Standards Association arranged permission to use certain drawings from CAN/CSA-Z262.1-M90, Ice Hockey Helmets.

Peter Fuller of Medieval Reproductions in Calgary, Alberta, provided the images of replica medieval helmets.

I've probably forgotten to thank someone and for that I'm truly sorry. Be assured whoever you may be, your help was indeed appreciated.



Foreword

I spent most of my career in the head protection field and when I thought about writing this book, it didn't seem that it would be such a big deal. However I was reminded that the history of the helmet is incredibly rich and diverse and to think one could cover all of it, is pretentious. The more I thought about it, the more I realized I'd better leave out discussions of head protection for fire fighters, police, and prison guards. In addition, military and aviation headgear has a rich history of its own that has been chronicled by others. I'd probably have to leave out considerations of various types of industrial headwear, bomb disposal technician's helmets and helmets intended for seaborne activities such as coast guard operations or powerboat racing. Helmets specifically for children had to be left out as this area alone could fill its own book. I finally decided I had better limit this overview to a few popular sporting activities. Two and a half years later, I realize that even now this work is incomplete.

Perhaps this book may be best thought of as a somewhat elaborate thumbnail sketch of how head protection in sports has come to be as it is after the beginning of this new millennium.

The first chapter looks at how helmets evolved historically from military and early aviation requirements, to the needs of the early motorcycle and car racers through to the modern helmets seen today in various sporting endeavors. Important technical developments and the contributions of the pioneers in the field are reviewed here.

Stating the obvious, perhaps, helmets have but one primary function — to protect against head injury. To do this, a helmet must somehow alter the consequences of a blow to the head of its wearer in such a way as to make it less injurious. What it comes down to, basically, is engineering a barrier between the wearer's head and whatever is trying to injure that head. Chapters 2 and 3 consider how to design and build a sports helmet. Various design principles are discussed as are some basic physics of impact as well as material and manufacturing considerations.

It's probably reasonable to suggest that there is far more art than science in helmet development but what science there is, is discussed in the next two chapters.

It may seem self evident, but one cannot properly consider the means by which helmets *work*, without understanding how various kinds of head injuries occur. In Chapter 4 we look at the mechanics of head injury from a technical (non-medical) point of view. We will simply regard the head as an elaborate, filled container that, when subject to some external insult, can be structurally *damaged*.

I guess it's pretty obvious to anyone who has briefly thought about it, helmets are different in different applications. Football helmets are different from those used by hockey players which are different from those used by auto racers or horse riders. Which brings us to the question, how do you know how well a specific helmet design will *work* in its own unique situation? Since no one's safety can be threatened by *live testing*, laboratory procedures for evaluating the protective capability of particular helmet designs have been developed and the *standard* methods are reviewed here in Chapter 5.

The sixth chapter is the *biggie*. It traces the art of helmet design in six major categories, auto and motorcycle racing, bicycling, equestrian activities, and skiing, as well as American football and ice hockey. The last part of Chapter 6 looks at some helmet designs used in less popular sports and at some designs you've not likely seen before. Some of these helmet concepts might well reflect how helmet design will evolve over the next few generations — and some are likely destined to become quite extinct.

The last chapter takes a look at some of the often frustrating yet amusing *warnings* and *instructions* that have accompanied helmets over the years.

Having gotten this far, I'm already thinking about a second edition, one that might fill in some of the blanks left here.

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1. A Brief History of the Sports Helmet

1.1 Combat and the Vulnerable Head

Protecting the human head from impacts is not new. Various forms of practical helmetry have existed for thousands of years. Consideration for head injury and protective headgear even appears in biblical writings with, among others, the seminal story of David and Goliath. As is well known, David brought down the unsuspecting giant with a well aimed, or fortuitously launched, stone to the temple. (It is unclear whether or not Goliath wore a helmet. If he did, it was apparently not very effective on this particular occasion). Before poor old Goliath *came to*, and to insure he never did, David subsequently dispatched the big guy by removing his head with his own sword. (At which point it didn't matter whether he'd been wearing a helmet or not.)

As legend has it, David had declined King Saul's offer to use the royal armor and helmet for this mission. A variety of reasons had been given to support his decision: *It's too hot, it's uncomfortable, it doesn't fit me, and anyway, I don't think it would help me that much*. This conflict between protection and *user friendliness* will continue for the next few millennia.

When weaponry changed from sticks, stones, and clubs to the metal variety, helmet design changed. The basic function of military headgear now became to protect the head, face, and the neck from the cutting blows of swords, spears, arrows, and other sharp and pointy things. The Assyrians and Persians, reasoning that cow and horse hide was obviously much tougher than man's, encased their heads and necks in hoods/helmets of leather. Some employed iron, but later on the Greeks developed something of a technological breakthrough with their elaborate full coverage bronze helmets.[1]



Replica of Greek bronze helmet with horsehair crest, Corinthian style. Classical period, 5th century, B.C. Worn by Hoplites of the Greek city-states. *Courtesy Medieval Reproductions.*

The Romans developed several forms of helmets, including the round legionary's, gladiator's and the centurion's helmet.

About the year 1200 the *helm* appeared. It was a flat-topped cylinder that was put on over a skullcap (or cervelliere) just prior to battle. At the same time, the skullcap developed into the basinet, with pieces added to protect the neck and with a movable visor for the face.



Roman Legionary helmet, "Gallic H" style. Steel with brass accents. First half of the first century, A.D. *Courtesy Medieval Reproductions.*

By the 1500s, several highly sophisticated types of helmets were in use, employing hinges or pivots to permit the piece to be put on over the head. They could then be fitted snugly around the head and neck to insure they would not be knocked off in combat.



Medieval Great helm, Pembridge style, c. 1375. Worn over a smaller helmet called a cervelliare. *Courtesy Medieval Reproductions.*

It seemed that the metal helmet was here to stay. But then came along the musket and, later, the rifle.
From the US Revolutionary War of 1776, through the battles within Europe, with Austria attacking Bavaria, France against Prussia, Britain's invasion of Denmark, France's attack on Portugal, and the US-Anglo War of 1812 to the US *Civil* War nearly 50 years later, combatants on both sides wore no more on their heads than fancy hats or simple cloth caps. Existing metal hats were of no help in stopping musket balls or bullets so *what's the point?* seemed to be the rationale.



Medieval bascinet with hounskull visor and mail aventail, c. 1390. *Courtesy Medieval Reproductions.*

The metal (steel actually) helmet reappeared, however, as a standard item for infantry in the opening years of World War I because it protected the head (somewhat) against the high-velocity metal fragments of exploding artillery shells. Apparently the French first adopted the helmet as standard equipment in late 1914. They were quickly followed by the British, the Germans, and then the rest of Europe. The *tin pot* tradition continued for most of the remainder of the twentieth century.

Infantry headgear such as that used in WWI protected against ballistic fragments to some limited extent, but in reality, like the more common industrial hard hat, its principal function was to help ward off assorted war induced debris falling onto the wearer's head. As such, the design was of a rather simple but specialized nature. The interior suspension, a kind of inverted hammock, served primarily to provide some limited fitting capability and to keep the metal shell from contacting the wearer's head. The *retention system* was a rudimentary fabric strap and a metal buckle.



WW1 steel pot infantry helmet. *Photographed by Stephen Fenn.*

The US infantry helmet of WWII, the M1, was somewhat more sophisticated having a metal shell that fit over a fiber inner shell in which the suspension was installed. The simple hard hat could thereby be converted to one with some ballistic capability at a moment's notice.



US M1 military helmet inner fiber shell.



M1 helmet with outer steel shell in place. In this case the outer shell is covered further by camouflage fabric.

Of course during periods of history when there were no wars, people continued to compete in games where different kinds of head injury threats were present — hence the need for sports helmets.

The most modern of infantry headgear has a single thick shell of multilayered ballistic fabric composite. The Personal Armor System for Ground Troops helmet is a heavy unit that does provide increased protection against ballistic fragments and versions of it are in widespread use amongst troops all over the World. It incorporates a chin strap arrangement that had previously been used mainly by paratroopers.



The PASGT infantry helmet. *Photographed by Stephen Fenn.*

1.2 Fighting for Fun

As comedian Jerry Seinfeld pointed out in one of his stand up routines, *"Humans had to invent helmets because they were doing things that could crack their heads open — and they chose to not stop doing them."*

Even children's literature contains examples of the importance of protecting one's head. You no doubt remember the young couple Jack and Jill. Jack, as is well known, *broke his crown* and, for whatever reason, *Jill came tumbling after*. Why they were going *up* the hill to gather water in the first place is lost in antiquity. In fact, we'll never know for sure why they went up there. What we do know is that Jack wasn't wearing protection (head protection) and sustained a nasty head injury. To treat the wound, he apparently *went to bed and bound his head with vinegar and brown paper.*

Franklin the turtle would not dream of getting on his bike (a turtle on a bike?) not wearing his helmet.[2]

So what exactly is a helmet? Well, if you look in a dictionary, you'll find a bunch of formal definitions including, *armor plate that protects the head, protective headgear made of hard material to resist blows, a defensive covering for the head,* and so on. The thing you notice about these definitions is that all have military overtones. Certainly in many ways, sports are a form of combat, civilized warfare you might say. However the kind of protection required by modern sports does not usually anticipate ballistic threats or the use of sharp and pointy objects (although you may think of some examples).

Sports in which protective headgear may be used, generally fall into one of *two* categories: a single accidental, potentially life-threatening impact, or multiple low level threats in games where getting hit in the head is more or less expected.

In the first category we have:

Auto racing, which includes all forms of car racing, open wheel, stock car, sprint, drag racing, etc., as well as on and off road motorcycle racing. Snowmobile and ATV racing would be included in this subcategory.

Ball games, which include, in North and Latin America and parts of the Far East, baseball, and in the rest of the world cricket. Neither sport till recently demanded meaningful head protection. Curiously they have different forms of protective headgear. So far, no one has suggested that basketball or tennis players wear helmets though eye protection is required in squash and racquetball.

Cycling. The sporting nature of this category includes road racing, BMX and mountain biking as well as time trials and pursuit racing. It also includes skateboarding and in-line skating (the threats are similar, just the wheels are smaller).

Equestrian. People have been falling from horses for a very long time. Until recently anything on one's head other than a cowboy hat or a show cap, was deemed unnecessary. Nowadays, helmets are used in all equestrian events like show jumping and eventing, and by jockeys in thoroughbred racing and drivers in standard-bred (sulky) racing. Rodeo cowboys still don't typically wear any form of head protection though plans are currently underway to fit helmets to the horse or to the bull he may be attempting to ride.

In the second category, we have:

Football. What is called football in North America is not what is called football in the rest of the world — though American football is starting to be played in many other countries. The North American kind has seen the use of some form of head protection since the turn of the 20th century. Only very recently has consideration been given to the head protection needs of the *soccer* player. Some rugby players have worn headgear for some time but it seems to have been primarily intended to prevent their ears from being damaged or ripped off.

Hockey. A sport once largely confined to the colder parts of the world (Canada, Sweden, and Russia, for example, though there were, in fact, hockey leagues also in England and France during the 1930s), it is now played all over the world. It's certainly no longer restricted to cold weather climes as illustrated by the fact that in 2003-04 the winner of the Stanley Cup, the epitome of hockey supremacy, was the Tampa Bay Lightning of that almost tropical locale, Florida. In the 2005-06 season, the Cup went to the Hurricanes of Raleigh, North Carolina. Though some form of hockey helmet has been used

since the early 1900s, widespread use of protective headgear was not common till the latter part of the 20th century. One could also include in this sporting category, because the nature of the game is so similar, the warmer weather variant of hockey, the national summer sport of Canada, lacrosse. In fact in Canada, where *box lacrosse* predominates, it is customary to wear hockey helmets. There is, however, no national standard for lacrosse helmets in Canada. In the US, the most popular form of the sport is *field lacrosse* and there is a helmet unique to this activity.

Skiing. Cold weather activities, in addition to recreational competition, slalom, and down hill racing, nowadays include snowboarding. That this falls into the category of head impact being *more or less expected*, as opposed to the *one big accidental hit* category, reflects the frequency with which amateur competitors fall down during slalom, downhill, and snow board activities. There can, however, also be accidental big hits (into trees, lift structures, etc.) in this sport so these too need to be considered.

In addition to the helmets in these two broad categories, there is a wide variety of other specialized applications where sports helmets are employed. These include bobsled and luge, hurling, martial arts, polo, short track and speed skating, ski jumping, skydiving and paragliding, and white water activities to name several.

1.3 Back to the Beginning: The Motorcycle Did It

The genesis of the sports helmet lies not in military lore but rather in the more mundane world of transportation.

In 1885, a German chap by the name of Gottlieb Daimler (yes, that Daimler), bolted a four stroke internal combustion engine, invented less than ten years earlier by one Nicholas Otto, to a bicycle and thus invented the first gas-powered motorcycle — but that was not the first motorcycle. That came nearly 20 years earlier. In 1867 an American, one Sylvester Roper, at the age of 44 adapted a coal powered, steam driven, two-cylinder engine to a wooden bicycle. *That* was the first motorcycle.

Regrettably at the ripe age of 73, Sylvester died while test driving a new motorcycle. It has been said that he was actually dead (he apparently suffered a heart attack) before he hit the ground so whether he was wearing a helmet or not is rather irrelevant.

At the beginning of the twentieth century other companies like BSA, Ariel, and Triumph in England, BMW in Germany, and Harley Davidson and Indian in the US arrived to fill a need for this new means of transportation. Of course, *boys will be boys*, and motorcycles and cars were being driven faster and faster, often in competition.

In June 1895, the *Chicago Times-Herald* newspaper announced the very first American motor car race. The racecourse route ran about 54 miles from Chicago's Jackson Park to Evanston and back and was run on November 28 that year. Though many *horseless carriages* had planned to be entered, when the race began, there were only six cars at the starting line. Two were electrics powered by batteries, three were gasoline-powered built by the German maker Benz, and one was gasoline-powered built by the American Frank Duryea.

The bad weather and extremely poor road conditions were too much for some of the cars and four out of the six had to drop out. Topping a high speed of 7.5 miles per hour, it took the winner, Frank Duryea 9 hours to win first place! The second (and last) contestant rolled in 2 hours later.[3]

The need for head protection had not yet arrived in motor racing.

Six years later, in May 1901, the first organized motorcycle race in the West took place on a 1-mile horse racing track in Los Angeles. Ralph Hamlin and his Orient beat three other riders to win the 10-mile contest in 18-1/2 minutes. By 1902, officially sanctioned endurance competitions were held, and in May of that year, the first road race in the United States took place between Irvington and Milburn, New Jersey (a distance of ten miles). Again, an Orient was the winner, achieving an average speed of 31 mph.[4]

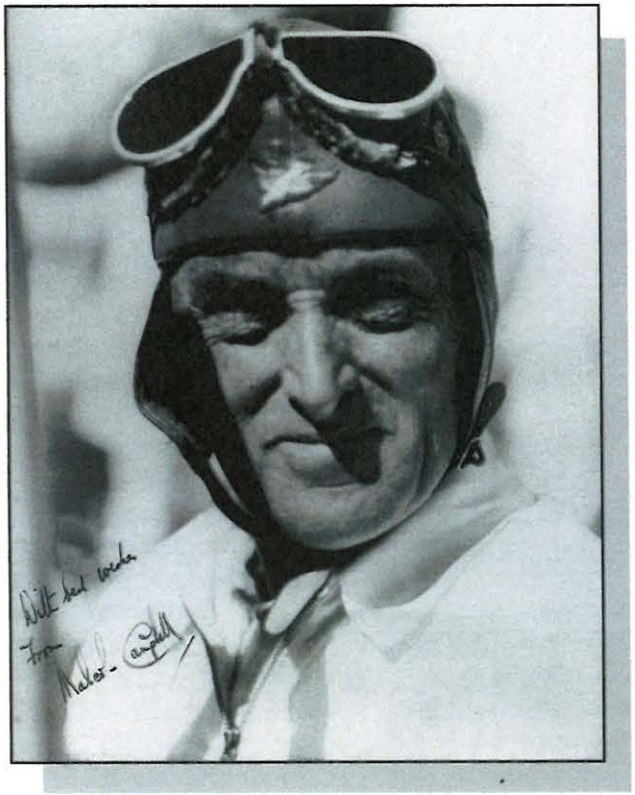
Crashing at speeds much faster than one could run, skate, or cycle, introduced the need for *crash* helmets — though that need would not be truly met for many years.

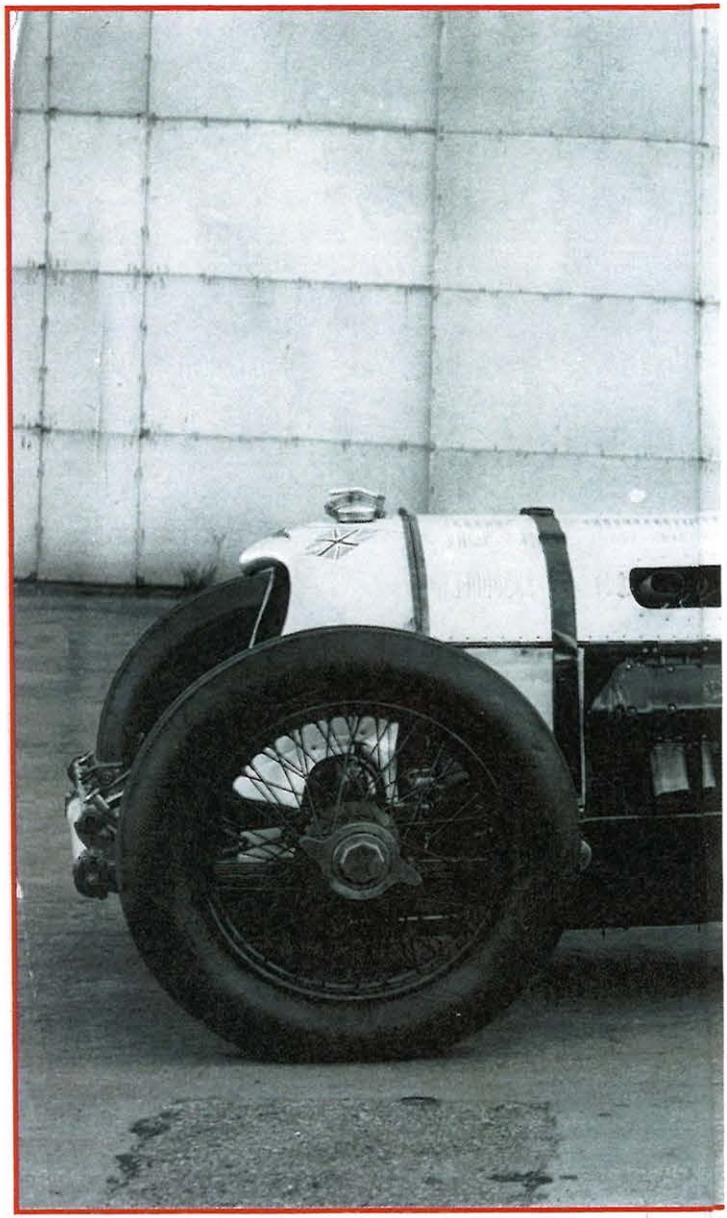
1.4 The Look of Leather

Initially *helmets* for motorcycle and auto racers were no more than leather bonnets. These designs, usually worn with goggles, were borrowed from earlier aviators and served primarily to keep the head warm and the hair in place.

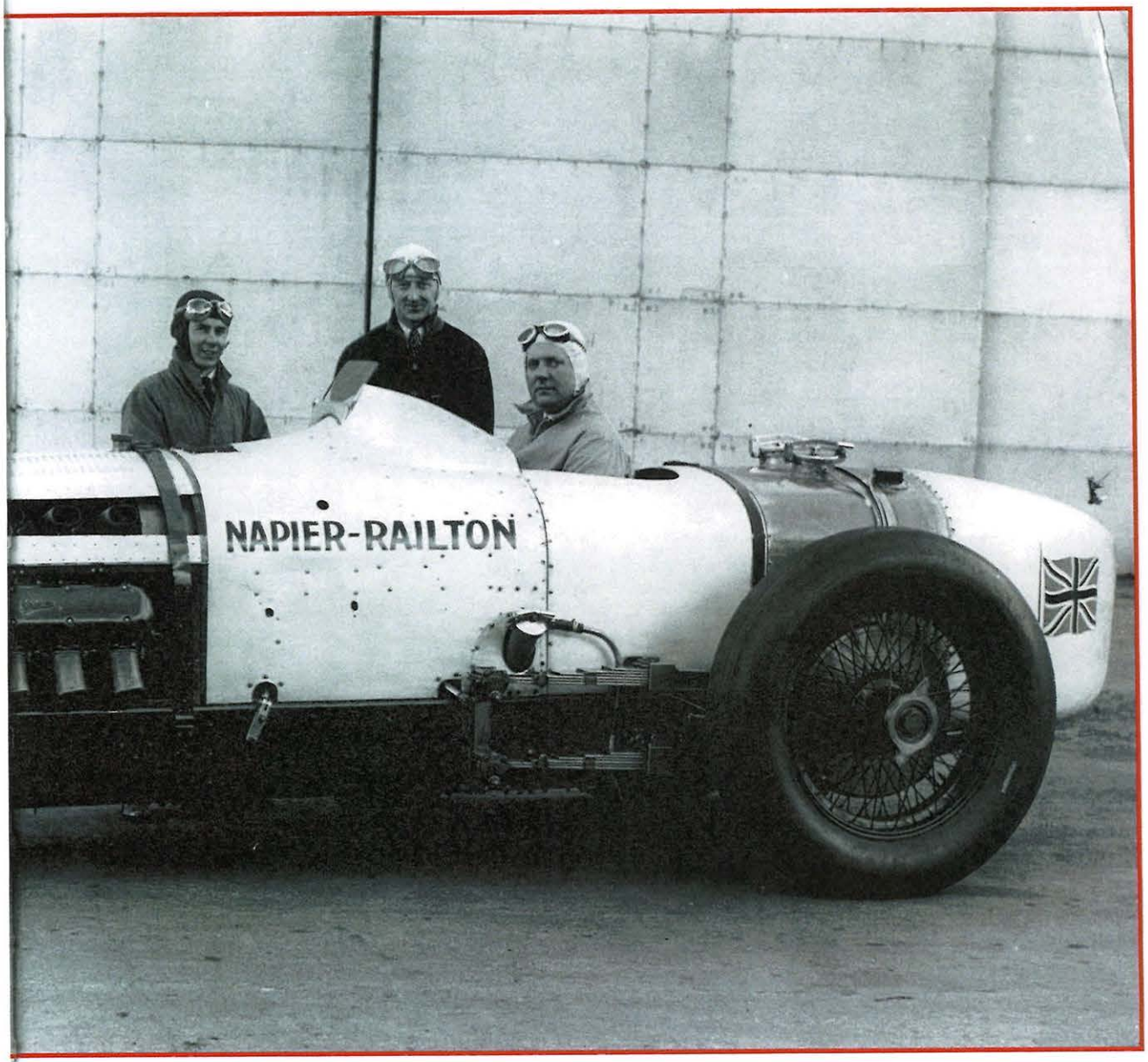
In the early 1900s, American football players also wore the equivalent of a soft leather hat. The more protective types employed a fleece or felt lining or were padded somewhat with cotton batting.

In motorcycle racing, head protection was largely a matter of what one could get hold of and football helmets were often used. One such racer, Maldwyn Jones, took the matter a step further. He designed a racing helmet seen here that was considerably better than the leather caps of the day. His helmet, while still leather on the exterior, featured a cork lining to reduce impact to the head in a crash. His design was a predecessor of safer helmets that would come decades later.[5]

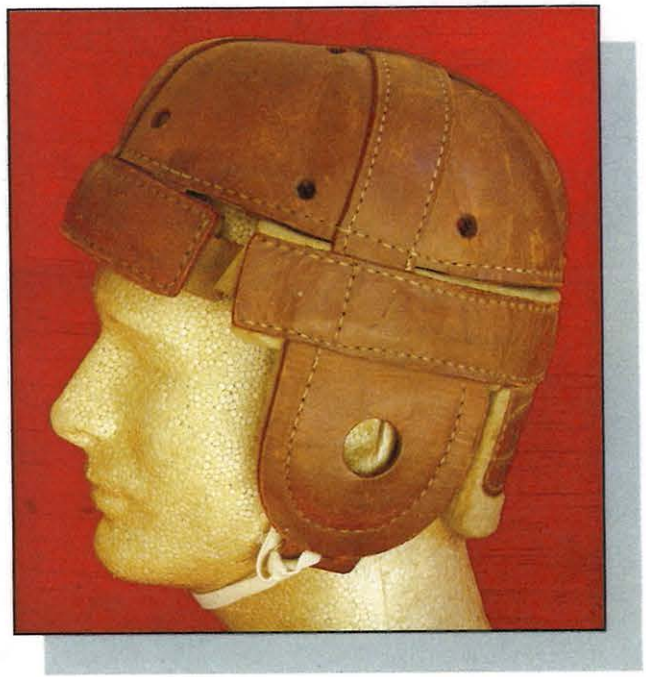




The English knight, Sir Malcolm Campbell, holder of numerous land and water speed records, is shown here after breaking the land speed record in the *Bluebird*. His signature bluebird appears at the front of his *helmet*. Campbell set nine new land speed records between 1924 and 1935. Among other firsts, he was the first man to exceed 300 mph on land. In addition to his accomplishments on land, in 1937 he set two new water speed records in the Bluebird hydroplane at over 125 mph. The following year he raised the record to over 130 mph. *Photo from the Varndell Collection.*

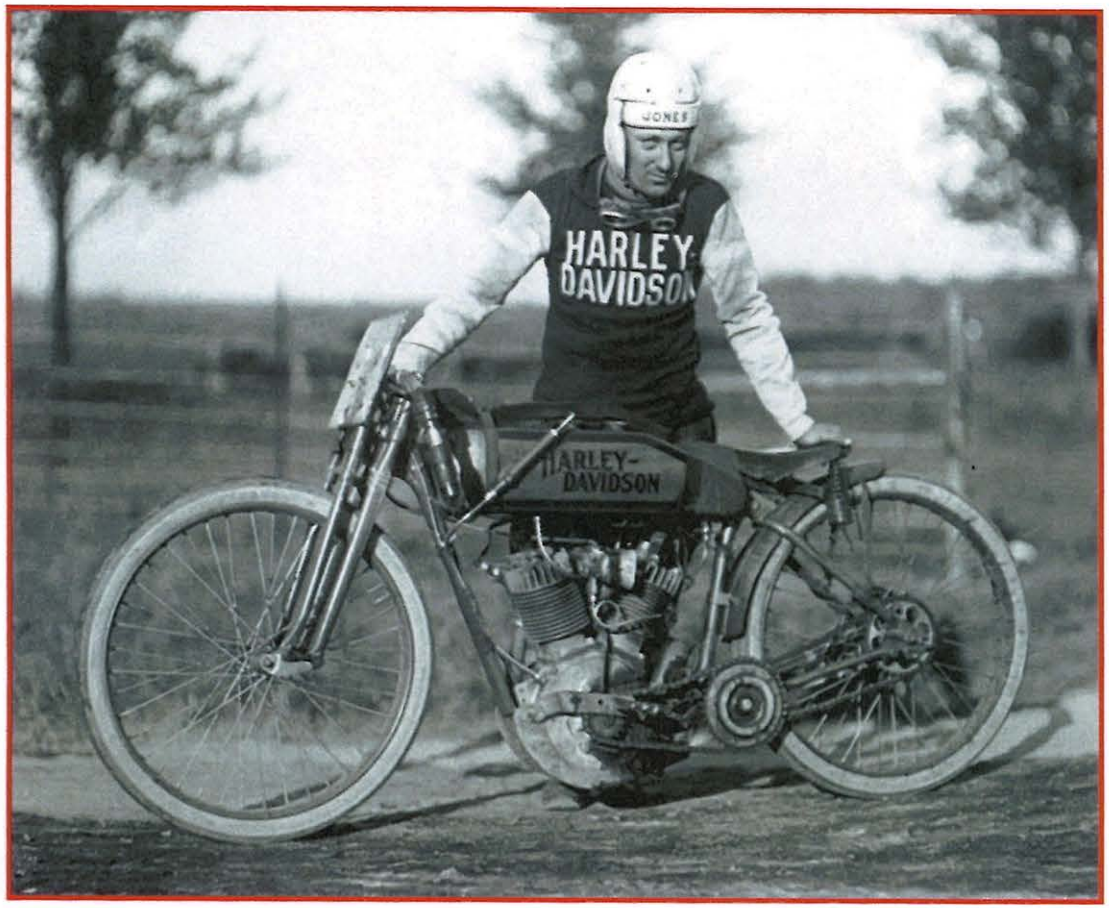


John Cobb in the record breaking Napier-Railton with friends all wearing period leather headgear c. 1935. Driving the piston engined, wheel driven Railton Special (not the car shown here) he set a new land speed record at Bonneville in 1939 at a speed of 368 mph. In 1947, he nearly achieved his goal of 400 mph and set a new land speed record of 394 mph. Like fellow Englishman Campbell, he also set records on the water. In 1952, he died at over 200 mph attempting to improve the water speed record at Loch Ness. *Photo from the Varndell Collection.*



A typical soft leather football helmet c. 1920. *Author's collection.*

As in football, getting hit in the head was not uncommon in that other popular sport, ice hockey. (Canadians and Americans will tell you the name of the game is *hockey*. Only Europeans make the distinction between ice and field). In the early 1930s the leather hockey helmet seen worn here by the late Eddie Shore, must have been produced in very limited quantities for very few players of the time chose to wear head protection.



Maldwyn Jones was a well-known racer and racing motorcycle builder of the 1910s and '20s. During the mid-to-late-1910s, Jones was perhaps the best dirt track racer in the Midwest US. *Courtesy of the AMA Motorcycle Hall of Fame.*



To quote from the Hockey Hall of Fame, Hockey Legends: "An imposing blend of raw talent and intimidation, defenseman Eddie Shore was one of the greatest ever to play his position in any era and his end-to-end rushes became every bit as famous as his crushing body checks and nasty disposition." *Photo courtesy Hockey Hall of Fame.*

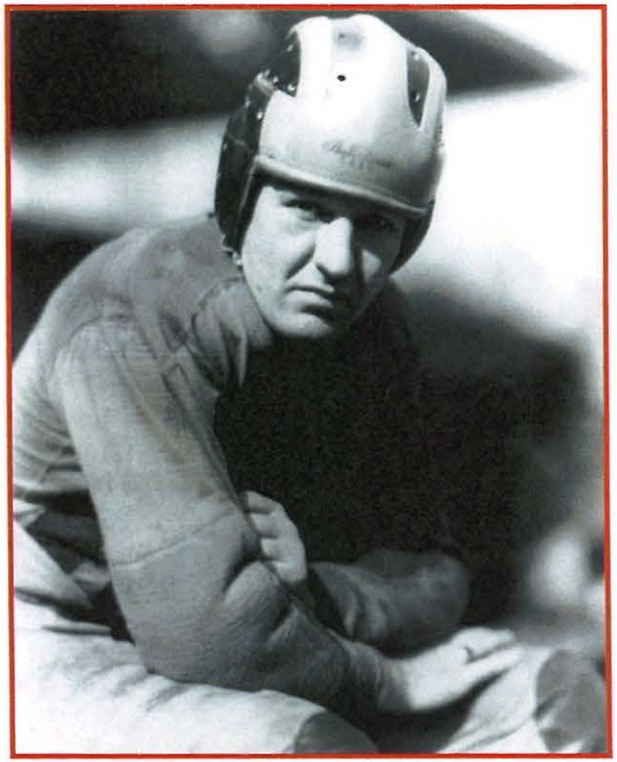
Improvements in leather headwear, however, were to come along. H.T. Gratacap, considered by many to be the *father* of the American firefighter's hat, had initially been in the ocean transit baggage business making luggage from specially treated leather. Being a volunteer firefighter in New York City, he and some of his buddies decided to try to provide firefighters with better head protection and developed the first hard leather firefighters helmet way back in the mid-1800s.

The hardened leather, known as cuir bouilli, was produced by first soaking the leather in water and then forming it to the intended shape. The shell components were then allowed to dry to the desired shape and then placed in an oven with beeswax. The wax melted and permeated the leather. When cooled down, the leather-wax combination hardened to its preformed shape. The process, essentially the same as that employed to make stiff medieval armor apparel, resulted in an outer shell that could withstand moisture as well as repeated blows before breaking down.

In American style football, concern for injuries dated back to the early 20th century. In 1905, for example, helmets were not typically worn and there were 18 deaths and 129 serious injuries.[6] Perhaps not surprisingly, later studies determined that most fatalities in football were due to head injury.[7]

As demands on the leather football helmet design increased, the outer leather was treated in a similar fashion to that of firefighters' headwear. Individual hardened leather pieces were sewn together and painted to make often quite decorative football helmet shells. Initially, they were simply lined with felt, fleece or some other padding but a few years later, with the introduction of a rudimentary inner suspension similar to that employed in early infantry helmets, something of a breakthrough in football headgear design had occurred.

This new device had the capacity to absorb and distribute blows to the head somewhat more effectively than the floppy leather caps previously in use. But there was still a long way to go. Football helmets were not even required in US college play until 1939 and not by the National Football League till 1943.



Harold Edward Grange known to most as *Red* also earned the nickname *The Galloping Ghost*. Considered by many to be the greatest football player of all time, the three-time All-American spent most of his professional career with the NFL Chicago Bears. Shown here in a hard leather helmet, c. 1930. *Photo from the George Brace Collection.*

1.5 The Hard Hat Approach

The first recorded use of a hard shell type of helmet in automobile racing in the United States was by Wilbur Shaw in 1932. Sir Malcolm Campbell had given him an English made then state-of-the-art helmet.[8]

The following year, in a race at Legion Ascot Speedway in Los Angeles, California, the helmet was credited with saving his life during a crash. Though claims such as this are rampant throughout the history of helmetry, (most are anecdotal and not based on any sound accident reconstruction or analysis) almost immediately the other drivers agreed to wear safety helmets while racing. Within the next few years the use of helmets by US drivers became mandatory.

Though the cloth or leather bonnet remained standard gear in aviation until the introduction of jet fighter aircraft in the late 1940s, by the 1930s the use of hard shell helmets in international and grand prix auto racing had become standard practice. The situation was similar in motorcycle racing. The very first of the modern hard *crash* helmet shells was not constructed of rigid leather but made up of several layers of cardboard held together with glue. Later, linen or other fine cloth impregnated with varnish resins was used. The sheets were laid up in a simple inverted dome-shaped mold and the *composite* was then allowed to cure to a solid shape. With a shape familiar to certain cookware, the name *pudding basin* was often applied to these early helmets.

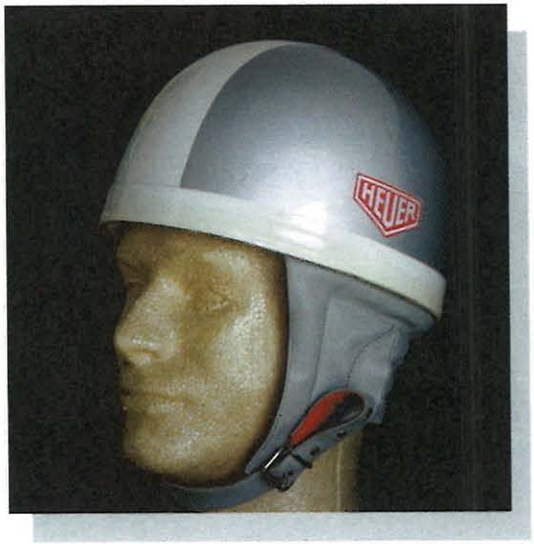


Wilbur Shaw won the Indianapolis 500 three times: 1937, 1939, and 1940. He placed 2nd in the race in 1933, 1935, and 1938. Shaw retired from racing in 1941. He was president of the Indianapolis Motor Speedway from 1945 till 1954. (*Indianapolis Motor Speedway photo.*

Why this approach was chosen over the hardened leather is uncertain. It could be that early designers in Europe where the vehicular helmet was evolving were out of touch with their North American counterparts. Or perhaps it was realized that the needs of the racer were in fact different from that of the athlete and that different approaches were required. At least one European manufacturer, the Bayard Co., did briefly produce a hard leather racing helmet in the late 1930s, but the style did not become widely adopted. Furthermore, some manufacturers of motorcycle and racing helmets actually covered their hardened fabric shells with leather (or vinyl coated fabric made to look like leather) thereby perhaps appearing to be made of hard leather, a practice that continued into the 60s. Sir Stirling Moss shown here wears a helmet typical of the era.

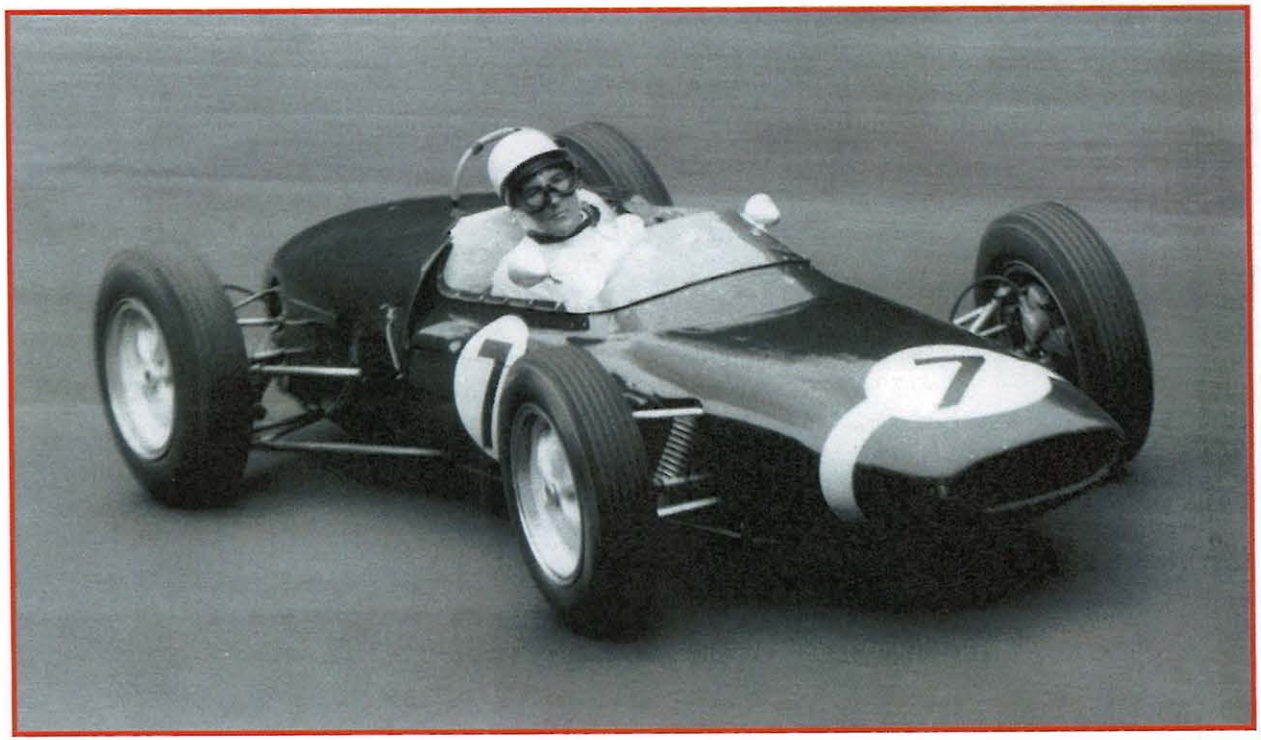


This French crash helmet is the only design known to use a metal shell. Advertisement from *The Motor Cycle*, July, 1956.



A Classic *puddin' basin* made in Italy by AGV in the 1950s, this being one of the first to sport a corporate logo. *Author's collection.*

Stirling Moss is seen here in the Rob Walker Lotus winning the 1961 European Grand Prix at Monaco. In those days, as seen here and in subsequent photos, the race car driver's head was terribly exposed and, in the absence of seat belts and meaningful roll bars, protection against head injury with a helmet made the same sense as it did for a motorcyclist. Thus it is not surprising that the helmets used in both endeavors were, and to a great extent continue to be, the same. *Photo from the Varndell Collection.*



The interior of these early racing helmets consisted of an adjustable fabric suspension system. Normal adjustment for any given size was typically provided by a drawstring at the top between the head and the inside of the shell. Side facial protection and retention of these *half shell* designs was limited to the leather harness. Cork and rubber padding inside the shell provided some minimal degree of shock absorption.

It must be remembered that an auto racing helmet and a motorcycle helmet were the same and both were such simply because that's what the manufacturers called them. There were no performance standards or specifications that defined what a *crash* helmet should be capable of doing in a crash. Many of the early helmet producers were in the hat business. They saw a developing market and basically made protective headwear that they thought would be better than nothing.

These *hatters* were mainly based in the English midlands. In the 1850s two of them James Everitt and Charles Vero joined forces and created a new company which in 1920 was renamed with the anagram EVEROAK, a most respected helmet manufacturer till the late 50s. Another *hat* company well known in the helmet business was Kangol. Founded in northwest England in 1938 to make military berets, Kangol no longer makes helmets, but is still in the hat business. KANGOL is an acronym (K for knitted, a-n-g from angora, and o-l from wool, and is identified by the kangaroo logo). Another famous British helmet maker, Cromwell, had been producing helmets since 1926 and was the last survivor of this industry in Britain when in 2004 it ceased production. The Cromwell name is now associated exclusively with head protection for fire, rescue, and police services.

In those early years, such entrepreneurs were eager to fill a need for head protection, but it would be a long time before any serious scientific approach to crash helmet design would occur. Curiously, perhaps, it was in the aviation field where these developments were occurring.



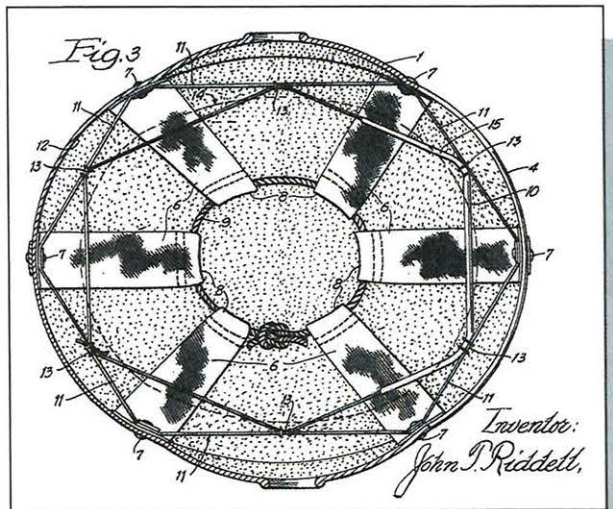
Advertisement from *The Motor Cycle*, September 1954.

1.6 Modern Innovations – Inventing the Good Stuff

If you've read this far, you already know that prior to the 1940s the standard aviator helmet was typically a soft leather bonnet. Then along came jet-powered aircraft. As the potential for buffeting in jet aircraft cockpits became evident, engineers began to devise enhanced safety headgear to protect the test pilots. Presumably impact to the head from interior structures posed enough of a threat to warrant these developments. The initial result was a number of hybrid designs that typically incorporated some form of hard dome-like crown attached to the upper portion of the standard soft fabric or leather flight helmet. These were typically constructed by private aircraft company personnel for their own use. Cork-lined auto racing helmets as well as hard leather football helmets were among those adapted for these interim designs.[9]

Meanwhile, the football helmet industry had made strides of its own. John T. Riddell, a former high school mathematics teacher and football coach, founded the Riddell Corporation in Chicago in 1929 to produce football related equipment. In 1939, Gerry Morgan and other employees of Riddell invented and patented a football helmet employing a molded plastic shell. Made of Kralastic® an ABS thermoplastic resin, the molded piece was tough and durable and could be readily mass produced. They were worn for the first time in a game by some players in the Chicago College All-Star Game of 1939. Unfortunately, early production methods were not that good and cracking of the plastic shells during game play gave plastic hats a bad reputation for the first few years.

In 1941, Riddell patented what he called a *Protective Shield Support*. It was not confined to use in helmets alone as the concept could theoretically be used for torso or extremity armor as well. For helmet applications, the ingenious arrangement of fabric straps, or slings, shown here in the original patent drawing, kept the rigid plastic shell off the wearer's head, and, far more importantly, provided a means for absorbing impacts to the shell.



Drawing from the 1941 Riddell Patent (US patent number 2250275).

Or as the patent itself states:

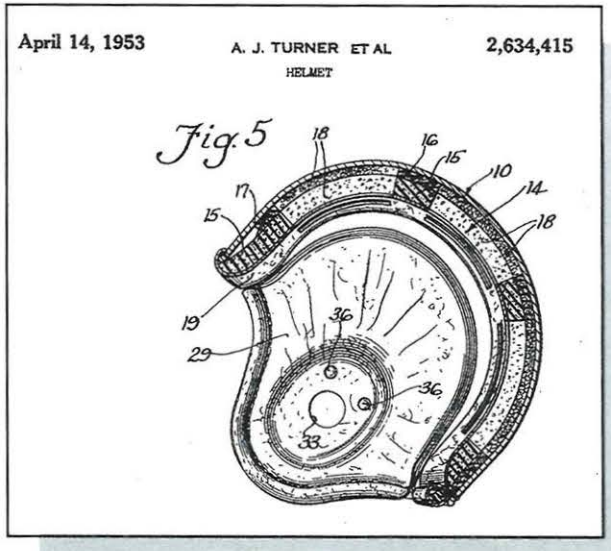
....a shock at any point about the surface of the helmet is not transmitted directly to the wearer's head in the vicinity of the blow but is transmitted by slings, and thus spread over a large area of the wearer's head.

What the patent doesn't exalt however is that this design provides more opportunity for ventilation than any close fitting design. The gap between the head and the shell — the stand off — provides a space where air can circulate and thereby help cool the wearer. Much more importantly, however, this is the first suspension type helmet design that provides impact attenuation to the front, back, and sides, not just the top of the head.

The eve of World War II, however, was not a good time to be coming up with new sports inventions. Football was not an essential industry and Riddell, among others, could not get plastic. But the military was going to need more helmets than they could have perhaps ever imagined.



Riddell suspension in US M1 infantry helmet.



The Turner padded helmet c. 1953. (US patent 2634415).

A subsequent patent was filed in 1941 by Riddell for a refinement to this concept that allowed the helmet to be better fitted to various head shapes and sizes through the use of an adjustable headband. He also incorporated what was called a neck sling, an additional set of straps below the hat band region under the rear of the head. Instead of football, Riddell's inventions were adapted to metal-shelled infantry helmets. Variations of it were used by literally millions of allied troops in what was at the time the largest production of helmets ever. The eventual demise of the leather football helmet was thus extended until the war ended. Coincidentally perhaps, the United States Military Academy football team of 1944 became the first team to wear plastic helmets with the new suspension design.

Riddell passed away in 1945 at the age of 59 and apparently never saw the application of his suspension design in the sports field. Following the end of the war, a new mass produced football helmet appeared on the market, becoming perhaps the second most recognized helmet shape in North America. Other sporting applications would, in time, pick up on this design concept. Many other football helmet manufacturers however took a different approach.

In a patent (US 2,634,415) issued in 1953 to A. J. Turner and J.G. Harvey of Wilson Athletics Goods Mfg. Co., the first padded hard shell football helmet was described. Claiming that *..tape or strap suspensions have been sadly inadequate to the avoidance of severe head jolts*, they proposed that a resilient closed cell, rubber-like foam be placed throughout the shell interior. Cavities in the liner aligned with holes in the shell were provided for ventilation.

Encased in leather, this liner inside the hard, molded plastic shell proved to be reasonably effective in dissipating impact energy and was the model for the current modern American football helmet. However, the design was very hot and heavy, and not well ventilated. As a result, the web suspension design continued to prevail for many many years — until more rigorous helmet performance specifications came along.

When the National Operating Committee on Standards for Athletic Equipment, NOCSAE, introduced formal specifications for the performance of football headgear in 1973, it was goodbye to the suspension helmet for good. Well goodbye in US football, though not elsewhere. In fact, to this day, the Riddell suspension is used in modern American military helmets such as the PASGT and as we'll see later, it was for a while employed in a variety of other helmet applications. Today however, as far as sporting activities go, the helmet suspension system is dead. Modern padding materials along with clever fitting and ventilation designs have relegated the Riddell suspension and its variants to the helmet historical dumpster.

While Turner was inventing the padded football helmet, developments in the military aviation field had not stopped. Research continuing after the end of World War II would find its way into the sporting arena.

Charles Lombard, of Northrop Aviation, Herman Roth, and Smith Ames working in the aerospace medicine field at the University of Southern California, also deduced that the Riddell-like suspension system, no matter how finely tuned, wasted space between the wearer's head and the inside of the helmet

shell that could be better utilized for impact management. Filed in 1947 and issued in 1953 (The same year the Wilson football helmet patent was granted), their patent (US2,625,683), would alter crash helmet design in ways that have basically not since changed. As their patent drawing below illustrates, their idea was to fill, as completely as possible the gap between the head and the shell with crushable, energy-absorbing material such as plastic foam. (Their patent actually refers to cellulose acetate foams but the early models apparently used a semi-rigid crushable polyurethane foam liner).

Clearly, even though the patent drawing shows the helmet upside down, energy absorption was improved, but this was a *one time only* kind of design since the crushing was permanent.

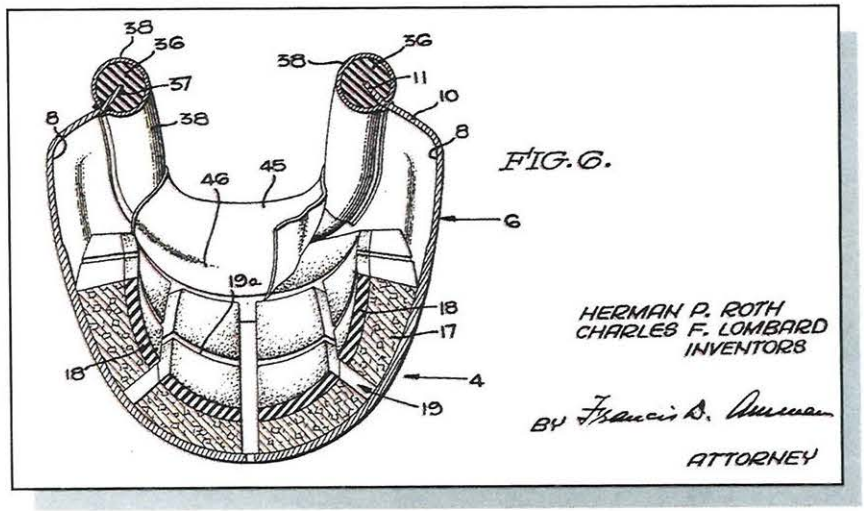
Originally, each aviator who was to wear such a helmet was custom fitted. One of Lombard's associates at the time, Harry Hurt (now Professor Emeritus of USC), recalls:

> *I remember fitting a friend from North American Aviation, who had just left the USMC and started in flight test at NAA. A nylon bag was fitted over his head and a couple of soda straws were placed in the nostrils so he could breathe OK. The nylon bag had thick shells covering the ears and making space for the earphones. Then the shell was fitted in place with a cotton rope damming and the formulated polyurethane was poured in. It usually took about 10 to 12 minutes for the polyurethane to foam-in-place and setup sufficiently to allow removal from the head. After overnight setup, the nylon head bag was pulled out and the helmet was hand-fitted to the user with comfort padding and edge beads, by the shop technicians. Then fittings for a face shield and oxygen mask retention, and a communications headset were installed with a final paint and trim.*

It wasn't until 1947 that the standard US Air Force full coverage hard shell helmet, the P1, was first introduced. Much the same as the European auto race helmets, the shell was made from pressure-molded cotton fabric and thermally set resin material. It was not until ten years later in 1957 when the P-4A variant became the first to adopt a laminated fiberglass shell.

Needless to say, these individual, custom fit requirements of the first Lombard helmets made them very expensive and beyond the pocketbook of most potential civilian users and immediate wide spread adoption didn't happen. Lombard recognized this and with partner Herman Roth formed Toptex Corporation in 1954. The plan was to mass produce helmets with crushable energy-absorbing polyurethane liners based on a standard headform shape. Importantly, at some point in time, a non-polyurethane liner material, expanded polystyrene bead foam, was selected for these helmets. This material, EPSB foam, was cheap, readily available, relatively easy to manufacture, light weight, its mechanical properties could be fine-tuned but most importantly, it crushed upon impact – and, more or less, stayed crushed.

The motorcycle, auto racing helmet as we



Drawing from the Roth-Lombard patent. (US patent 2625683).

know it today was born. To this day, virtually all helmets of the *vehicular* genre (i.e. crash helmets) employ this very same material. Not every manufacturer of helmets switched to EPSB foam liners right away but eventually, all did.

As Harry Hurt again recalls:

> *If there is any credit or blame for EPS in helmets, I would expect that genius Herman Roth .....to come up with that idea. I remember Uncle Herman always had a desk top covered with junk from the shop, and I recall talking with him about the Japanese cameras then being shipped in custom molded Styrofoam set up just like the helmet fitting. He took the shipping pack from my brand new Petri Pentaflex camera and started whacking on it for some test materials. Herman was a real genius, a quality person, and I know that Dr. Lombard counted on him to come up with the solutions to all the problems.*

Individual fitting of these helmets was to be achieved via a leather adjustable hat band. Later models used a soft pliable *comfort* foam liner to accommodate a range of head shapes and sizes. Toptex's initial production run in 1955 was for motorcyclists for the Los Angeles Police Department. Later the police style helmets were marketed, *for everyday use of (the) working rider*.[10] Hardly widespread adoption, but then along came Roy Richter.

A pattern maker and part time race car driver, in 1933 Richter had gone to work for a small auto parts shop in the Los Angeles suburb of Bell, California. Although an avid and briefly professional auto racing driver, Richter became better known for his work in designing and building winning race cars. In 1945, Richter bought Bell Auto Parts and amongst the auto *speed equipment* he provided to his customers, were auto racing helmets. Of course at that time, the only helmets available were those cork or rubber lined pudding bowls. Then in 1946, one of Richter's close racing associates Einar *Swede* Lindskog was killed in a sprint car race and Richter began working toward better racing safety equipment.

In 1954, Richter and company designed and began to manufacture their own helmets in a garage behind the Bell Auto Parts store under the guidance of one Vern Hancock. The initial helmet shells preempted the military flight helmet designs and were hand laminated fiberglass resin composites. (They weren't the first however. As early as 1948, Cromwell in England was producing motorcycle helmets with a fiberglass shell).

Following the lead of Lombard's aviator helmet design, a thick resilient foam polyurethane liner was employed. Along with its extended coverage of the head, the Bell 500 was believed to be among the most protective race helmets ever designed.



The helmet shown here, painted by Verne Hancock in the colors of the Long Beach Millikan High School Rams, is one of only two Bell 500 known to still exist. *Ryan Parks photo, courtesy Bell Sports Inc.*

Motorcycle and auto racing helmets were beginning to make significant strides. However, the racing community was to enter an era of enormous progress in head protection through the death of yet another of its fraternity and the intervention of one very special physician. As Vern Hancock recalls:

> *There was very little science in those early days, common sense ruled. Except for a guy named George Snively MD. George was involved in sports car club racing in the 1950s and had seen enough common sense helmets to realize something needed changing. Armed with X rays of cracked helmets and skulls (produced with the cooperation of several cadavers) George approached the various manufactures of these helmets with the test results. None of the other helmet makers responded to this information. Roy Richter (owner of Bell Auto Parts and Bell Helmets) called me (head of the helmet division) into his office for a "what to do" conference. After a short meeting, he elected to stop production 'til we could get more info.*

Who was this MD that brought this industry to a halt and on what basis?

George Snively studied chemical engineering at the Johns Hopkins University before obtaining his Doctor of Medicine degree from the University of Pennsylvania in 1945 and after a brief stint in the military, joined the Medical Faculty of the University of California where he remained a Professor in the School of Medicine until his untimely death in 1983.

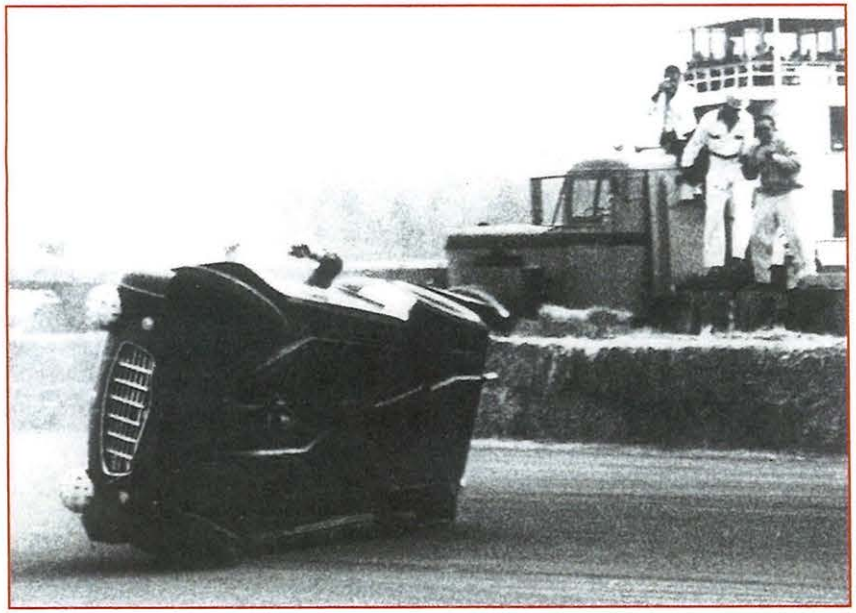
Shortly after joining the university, he embarked on another passion, amateur sports car racing. George was present in 1956 at such a race when his friend William "Pete" Snell died from head injuries suffered in a racing accident.

Subsequently, the Pete Snell Memorial Fund was set up by the San Francisco Region of the Sports Car Club of America. With the Fund's backing, Snively decided it was time for a somewhat more realistic look at some of these so-called crash helmets. In retrospect, Pete Snell probably died because of the absence of any roll-over protection structure in these early racing cars rather than from an inadequate helmet. When Snell's TR2 rolled upside down, his head, no matter how well it may have been helmeted, sustained a mighty blow. Nowadays, integral roll-over structures, formerly simply called *roll bars*, are mandatory in all forms of auto racing. Had Snell's car been so equipped, he likely would have avoided these head injuries — and improvements in helmet design may have stagnated for many years to come.

Snively undertook a study that had never before been contemplated, a study that could only have been conducted at a medical facility. In its July 1957 edition, *Sports Cars Illustrated* published what the editors called "what may be the most shocking article you've ever read." (Obviously this was long before the tabloids had even dreamt of Michael Jackson). In that article, Snively, then the Director of the Department of Medicine at Sacramento County Hospital, discussed his testing of helmets then currently available to the racing community. The perhaps overly dramatic title of the article, *Skull Busting for Safety* was likely suggested by the editors rather than by Snively.

In what must be considered one of the most bizarre yet important experiments of its time, Snively had helmets placed on the head of cadavers (presumably from the anatomy lab) and subjected each to a massive impact. Six cadaver/helmet experiments in all were conducted on six different brands of helmets then available. In every case but one, the helmets failed to prevent the cadaver head from sustaining what would, in a living human, be a life threatening skull fracture. The helmet from Bell, the 500, the Cromwell, an aviation hard shell helmet made by Gentex, as well as models produced by McHall and Anderson all failed Snively's impact test.

The only helmet to not result in a skull fracture was the police helmet being made by Lombard and Roth's company Toptex. Though all helmets tested had a hard outer shell, this was the only one with a non-resilient EPSB foam liner and it was the one that would change the face of auto and motorcycle racing, cycling, and equestrian helmet design over the next 50 years.





The sports car crash that started a helmet revolution. *Photographs courtesy of the Snell Memorial Foundation.*



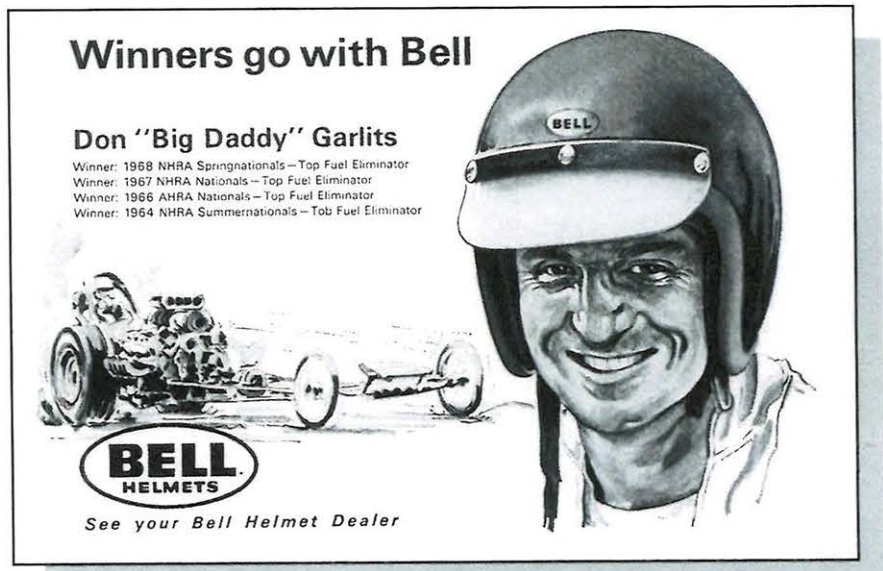
Bell subsequently licensed the Lombard patent, introduced the EPSB liner to its helmet and, with a stronger retention system, the 500-TX line of motorcycle and racing helmets was introduced in 1958. They and nearly every other helmet producer have been making them that way ever since.



The Toptex *police style* helmet c. 1955. *Author's collection.*

For many, many years, head protection in other areas was not even contemplated let alone required. Those early innovators could not have guessed the broad influence the results of their pioneering efforts were going to have. Helmet developments in other sports where head injury could occur: skiing, baseball, soccer, rugby, cricket, and, later, skydiving, snow and skate boarding, water skiing, the martial arts, BMX, ATV and snowmobiling, etc., were simply adaptations from the auto/motorcycle racing, military, and athletic fields.

By the mid-fifties, the future design of protective headgear was taking shape. During the sixties, seventies, and eighties, helmets generally improved somewhat in North America, but less so in Europe and elsewhere. In Europe the fuller coverage of the *jet style* helmet was adopted but the interior impact energy management system was not much better than it had always been.



Big Daddy endorses Bell in this ad from the late 1960s.



A jet-style helmet made by the Italian firm AGV, c. 1960. Helmet has a fiberglass shell and modern chin straps but impact protection is limited. The way the helmet sits high on the head by today's standards, is because of the emphasis on impact protection to the top of the head and not the side, front, or back. *Courtesy of good friend Laurin Garland.*

The most, and perhaps one of the last, significant developments in motorcycle and auto racing headgear came in 1966 when Bell introduced the first full facial coverage helmet, the Bell Star. Initially it was developed for dirt track motorcycle racing to improve facial protection from stones and clumps of dirt being thrown up from other bikes (*roosts* to the well informed). Previously this had been dealt with by clip-on mouth guards and goggles.



AGV jet-style interior with classic draw string harness system and minimal cork padding under leather hat band.

The Bell Star revolutionized racing head protection in ways that perhaps no other safety device, except the roll cage and the seatbelt, ever achieved. Today, when Carlos Montoya races in NASCAR, or Paul Tracy in CHAMP car or any driver in any other sanctioned automobile race, as well as riders in virtually any kind of motorcycle road racing, they *all* wear a full-face helmet based on this original design concept.

And in *off-road* motorcycle racing, Bell can be credited with yet another innovation — the Bell Motostar. In 1975, this was Bell's offering of the Star back to the motorcycle world with a design reminiscent of the old style mouth guards and which allowed the familiar pair of goggles to be worn – but which provided far superior protection of the face against the *roost*. It became a very popular design and was adopted by many manufacturers.



The original, somewhat beaten up, Bell Star shown here had a transparent face shield that was fixed in place, a feature that did not last very long. It was soon replaced by a flip up shield. *Ryan Parks photo, courtesy of Bell Sports.*



A typical modern *dirt bike* helmet complete with the stylish peak is shown here, the KBC Hurricane.

The next significant innovation in the field came from bicycling in the late 1980s. The shell-less helmet was a revolution in headgear design. For the first time since the soft leather bonnet at the turn of the 20th century, a helmet came along that had no hard functional outer structure. The thin *micro-shell* allowed helmets to have a weight that would have been unheard of before. It, probably more than any other factor, accounted for the current widespread acceptance of the modern bicycle helmet.

So there it is, a brief history of invention, research, innovation, and adaptation that brought us where we are today in the field of the sports helmet. But hey, how does one actually design a helmet anyway?

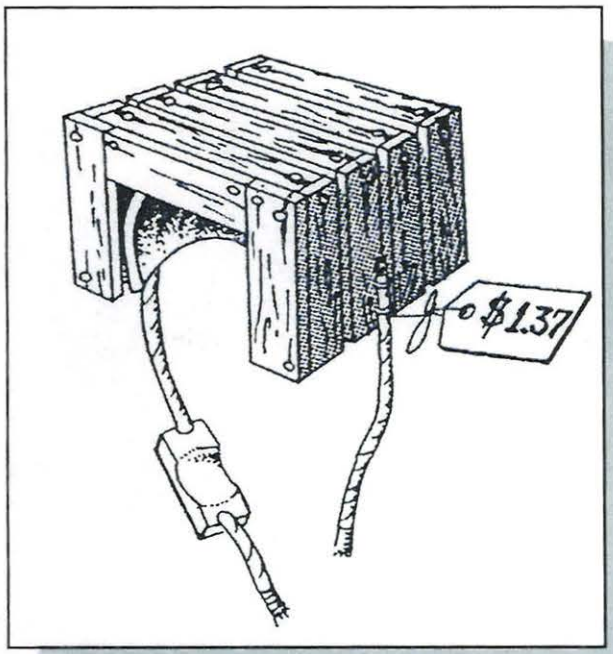


A modern bicycle helmet the Vigor Fast Traxx.

2. Helmet Design - Some Principles.

So you wanna be a helmet designer? Or may be you're just interested in how it's done. Well some aspects of it are pretty straightforward. Some are not quite so easy. As with most products, design specifications, in general, can usually be broken down into two categories: **performance** and **user** requirements. In the case of a helmet, the former makes it *work*, the latter insures that it is acquired and used.

Let's start with the easier ones first. What the user wants, but which have little to do with actually protecting his head.



A somewhat sarcastic view of *The Helmet as Seen by the Manufacturer.*[11]

2.1 User Requirements

User requirements have to do principally with personal factors related to whether or not the helmet is considered acceptable by the wearer. These sometimes vague *human factors* are the ones that an individual who is considering using the device might take into account before ever actually taking a shot in the head. What's it cost? How does it look? Is it comfortable? These are typical user issues that will determine if a design is to be a success.

2.1.1 Value

The price of a helmet might be a few dollars for a mass-produced bicycle helmet to several thousand dollars for, say, a fully equipped Formula racing car helmet. No matter the price, it is an important factor designers must obviously consider. If in fact it is judged to be too expensive (i.e. not enough value for the money), the unit will go un-purchased. Many otherwise excellent designs have died on the drawing board or on the store shelves because they were too costly too compete or just didn't seem to be *worth it*.

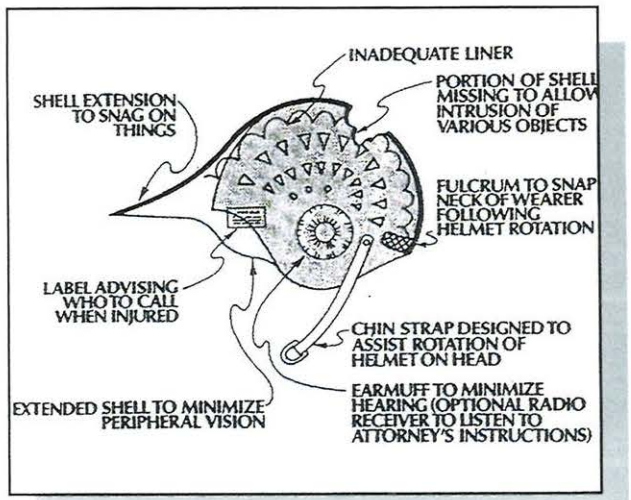
At the same time, many expensive helmets don't cost much more to produce than cheaper versions. The price of a bicycle helmet for example can range from $10 to several hundred. And it's absolutely true, an expensive helmet may well protect you no better than the *on sale* special.

Like any consumer product, the price reflects what it costs to design, produce, market, and distribute the product (and of course the profit the company is trying to generate). In today's litigious society the price also includes a significant component to cover future product liability costs. At one time Riddell reported that fully one half the cost of its football helmet was related to liability claims issues. The cost of law suits has put many a helmet producer out of business. One well known Canadian firm manufacturing hockey helmets went into receivership after losing the first time it was ever sued. As the cartoon below suggests, there is no end to the *defects* that can be alleged in a helmet design.

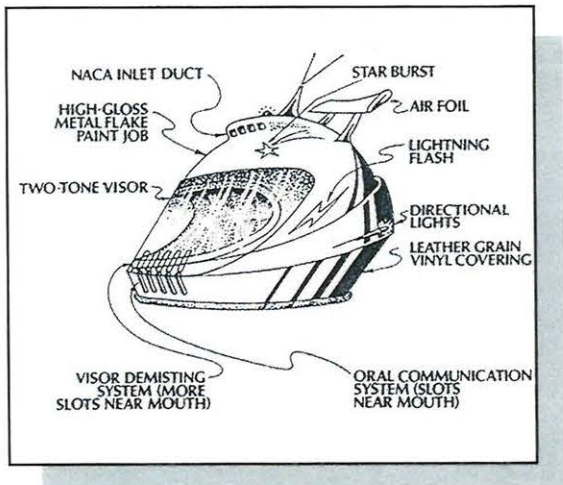
2.1.2 Appearance

Good looks are surely in the eye of the beholder. A helmet wearer cannot, without a mirror, see how he appears in his helmet. However, unless he is somehow obliged to wear whatever is provided (see soldier, firefighter, police officer, etc.), a *proper* appearance of the helmet is crucial to the success of the design. A bicyclist's helmet cannot look like a hockey helmet any more than a full-face motorcycle helmet can look like a football helmet.

While it remains true that *form follows function*, some aspects of the overall design of helmets in various fields have evolved in much the same way that different clothing fashions evolve, for no reason other than to simply look different. At the same time, tradition also dictates the limits to which *fashion* can go. In the protective headwear field, however, it is not the fashion designer but rather the industrial designer that rules.



The Helmet as Seen by the Product Liability Lawyer.[11]

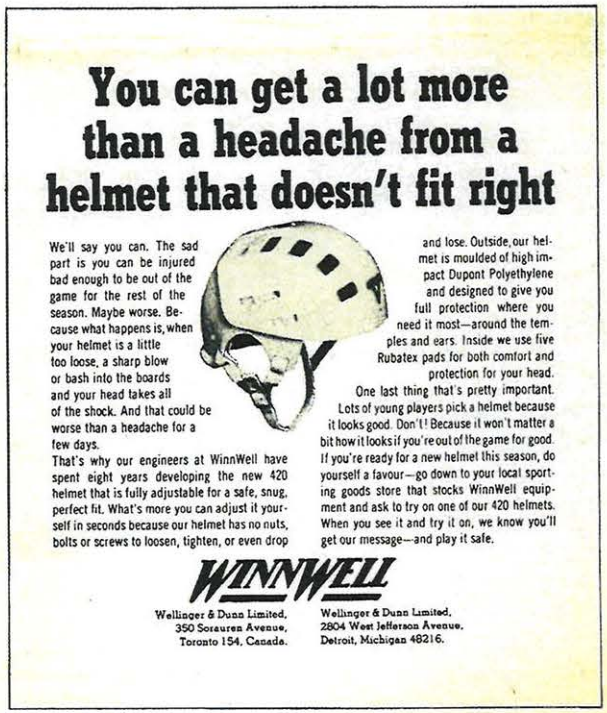


The Helmet as Seen by the Industrial Designer.[11]

The industrial designer has responsibilities that go way beyond how something looks — but it is a significant part of that profession. With the exception of the *directional lights*, many of the styling features shown in this old cartoon have in fact been realized in modern designs.

There is of course the matter of *team* helmets. Individuals are not going to have much of a say in how their helmet is going to look — it will look like pretty much like everyone else's on the team. That was certainly not always the case. Players on hockey and American football teams may not have worn a helmet at all in the *old days*. Later, whatever one had available or perhaps what had been paid for by a manufacturer to be worn, led to a considerable variety of headgear designs (and even colors) on the different heads of players on the same team. Hockey helmets continued to compete for the right *look* and nowadays they have come to look all pretty much the same — though if you look closely you'll see that there are several different designs out there.

One not-so-popular hockey helmet from the 1960s, the Winnwell 420, was supported by the advertisement below, which suggests that players should *not* buy a helmet that looks good! Doesn't say much about the perceived attractiveness of their design eh?



Early advertisement for Winnwell Hockey Helmet.

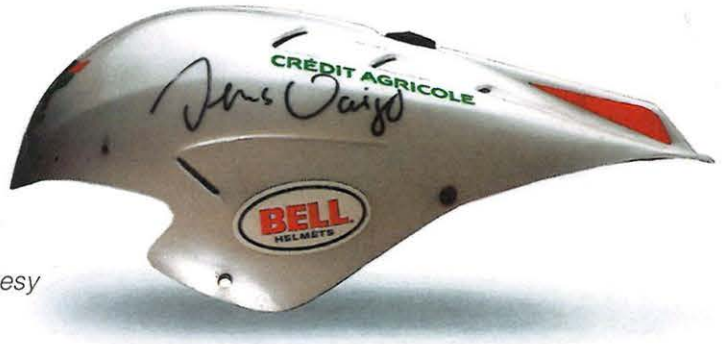
Though there is no uniform appearance for them, most people would now recognize a hockey helmet as being such and would not confuse it for, say, a skiing helmet. And the American football helmet shape has become so iconic that even if a far superior design could be achieved, the appearance of the helmet would have to remain essentially unchanged. As in many other endeavors, what looks right may be a reflection of what ones heroes are wearing. Several good hockey helmet designs have failed commercially because no one in the NHL was wearing it. The stars of bicycle racing and motocross also influence the helmets bought by young competitors.

In the case of Wayne Gretzky, the *Great One,* hero worship did not encourage sales of the Jofa helmet he wore throughout his career. It was a design from the sixties that could not meet prevailing standards in North America and could not be legally sold in Canada.

In cycling, styling is dictated by the need to ventilate the head. In addition, *streamlining* has become something of a fashion statement in helmet design. It has never been shown that streamlining could ever significantly improve a cyclist's performance. Still, even a 1% reduction in overall drag could produce a one mile advantage in a 100 mile race. In bicycle time trials very exaggerated tear drop helmet shapes may reduce drag but compared to the rest of the man-machine combination, the effect is probably more psychological than aerodynamic.



The *Great One*, Wayne Gretzky. *Photo courtesy the Hockey Hall of Fame.*



An aerodynamic fairing worn by Jens Voigt in the 2002 Tour d' France. *Ryan Parks photo courtesy Bell Sports.*

In automobile racing, a slightly different tack on streamlining has been seen. The *spoiler* suggested 30 years ago in the earlier cartoon, actually showed up in the early 2000s as a *wicker* on a number of different racing helmet designs. In addition, a front lip, or spoiler, such as seen below has been introduced. Neither is intended to make the wearer go faster but rather to reduce turbulent buffeting around the driver's head and to stop the helmet from *lifting* at high speeds.



Juan Pablo Montoya's F1 racing helmet shown here has three aerodynamic additions, the front lip, a *wicker* at the top and a rear spoiler. Also seen are the transparent *tear-offs* on the visor used to clean up the field of view from time to time. *Courtesy JMJ Auto.*

Helmet worn by Jeremy McGrath, 7 times World Supercross champion. The graphic design is by the legendary Troy Lee, but the tassels were apparently Jeremy's idea. *Ryan Parks photo courtesy Bell Sports.*

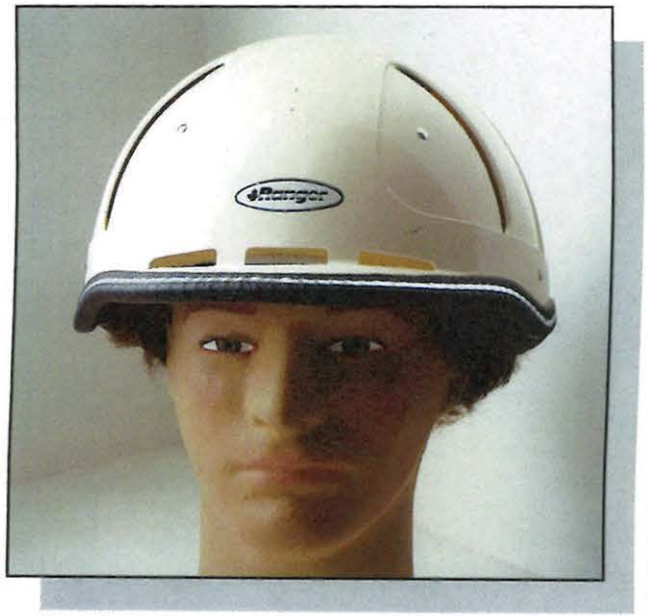


And no matter what the application, remember (as do professional race car drivers for example) about providing for graphics, in most cases, the flashier the better. Appropriate graphic designs on crash and athletic helmets can go a long way to making a design a success. In addition, it can be a marketing factor. As an example, a girl's skateboard helmet may well be the same as a boy's except for the cute doll graphics on a pink background. Some wearers use special graphic design on their helmet to express or identify themselves in unique ways.

2.1.3 Comfort and Convenience

In the end what makes a helmet look good is a difficult design issue. The first of the modern bicycle helmets often made people feel like they looked like *mushroom heads*.

What will look good in the year 2100 is anybody's guess.



A Canadian made Ranger cycling helmet from the 1970s that helped perpetuate the *Mushroom Head* look. *Author's collection.*

It seems that most people are willing to tolerate a certain level of discomfort or inconvenience in order to achieve the benefit of a protective device. However, it is obviously true that an uncomfortable helmet will not be worn cheerfully and, given the option, the wearer would choose no helmet or one that *feels better* on his head. Like appearance, comfort is such a subjective matter that it is difficult to identify comfort design requirements. Convenience, in the absence a *hassle meter* is equally difficult to quantify

Aside from weight and ventilation considerations, which are next discussed, the principal comfort feature is *fit*. If it doesn't fit right it won't feel right. A good helmet fits so well and feels so comfortable that one forgets it is being worn. Achieving this good fit may require adjustability as well as a soft *comfortable* interior.

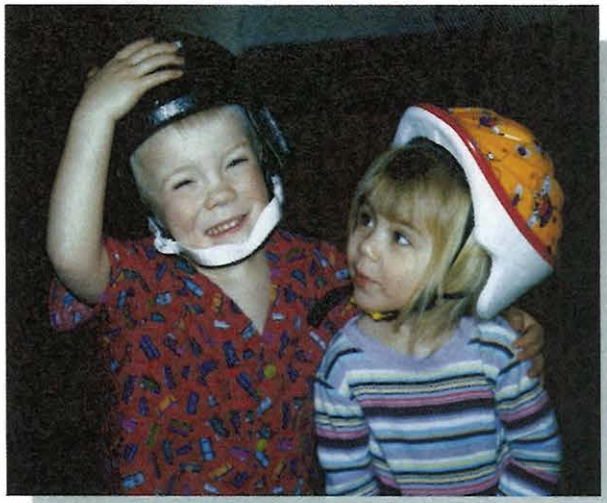
Auto and motorcycle racing helmets typically have no means to adjust the fit on the head. With few exceptions (a few high-end motorcycle helmets come with different size cheek pads that can be installed in the helmet by the wearer), the helmet is manufactured to a specific size or size range and that's it. It is very apparent, therefore, that a potential buyer of such a helmet take the time and trouble to personally *fit* the helmet of his choice. If it doesn't *fit* or feel comfortable, it should not be purchased because there is no practical way to improve this situation.

The overall size and shape of the helmet is governed by the shape of the shell and the impact liner. The fit is dictated by the *comfort padding* which is secured to the interior of the helmet.

Think about it for a moment. There are millions of folks out there that might wear your helmet. Their head size can range from XXS to XXL and if that weren't enough, their shapes are different too. *Fitting* a helmet may not seem to be a big deal but it is. Consider children. Their head shapes are not simply those of miniature adults. Their head shapes are uniquely different. Many parents will know how difficult it can be to properly fit a kid's head because many a child's helmet often has such poor *anthropometry* (i.e. its shape isn't very human like). The author's grandkids below are typical of kids wearing kid's helmets that don't and can't fit properly.

Consider too the ladies. Not only are their heads typically smaller than men but their head *shapes* are different as well. Women's hair is also an important factor in how well the helmet fits and how comfortable it may be. Some might wear a helmet that is dangerously too big because it might flatten their coif leading to the dreaded *helmet hair.*

In baseball, a nod is given to the fairer sex and the fact that some ladies wear their hair in ponytails. Here one manufacturer takes two somewhat different approaches to the matter.

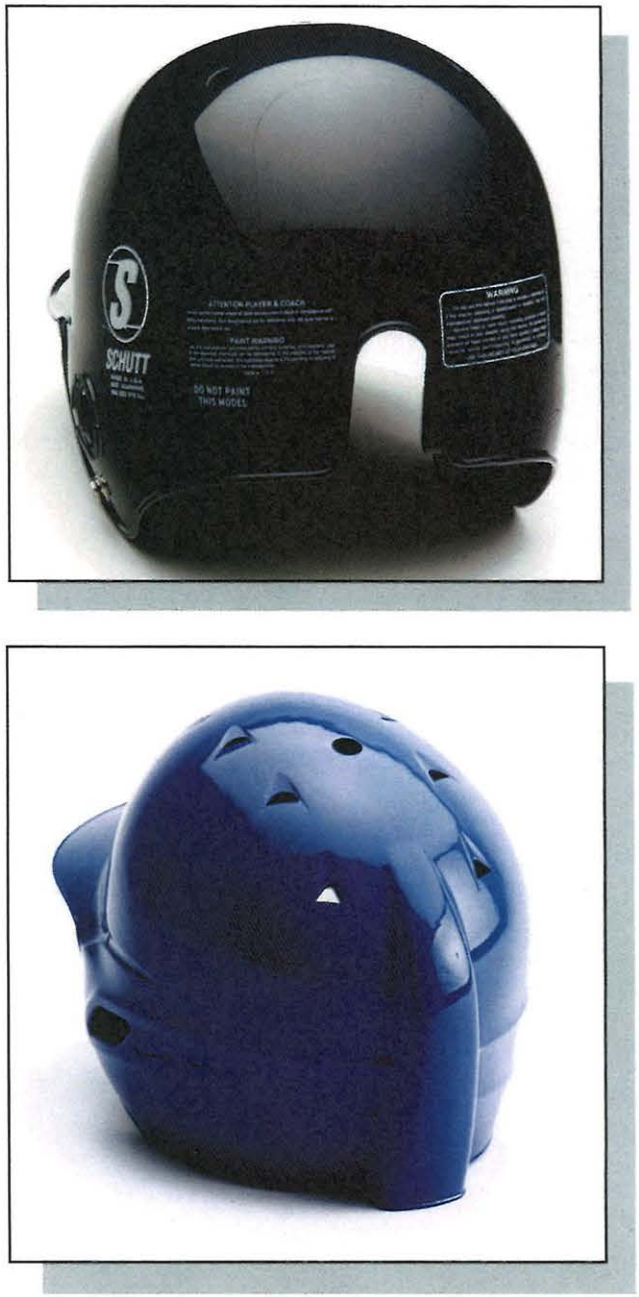


Owen and Abby just can't get a good *fit. Photo courtesy of Mom and Dad Rolleman.*

And yes, even race has a bearing fit. Asian heads are a different shape than those of Caucasians for example. At least one manufacturer of motorcycle helmets has two different interior shape geometries, one for Europe and America and another for Asia.

How convenient can it be to have to wear a helmet anyway? Aside from trying to figure out what to do with it when you *don't* need it, probably the greatest inconvenience is getting it on and off. *Donning* and *doffing* as they say in the trade. And the most inconvenient part of that is fastening and unfastening the device that holds the straps together (except as above in baseball where usually no chin strap is used). And if it's so inconvenient a wearer is likely to not fasten it at all, we have a big problem.

Other inconvenience factors might include having to adjust the helmet to fit and adjusting the straps to insure proper positioning on the head. This may have to be done when fitting the helmet for the first time, but the aggravation can sometimes be excessive. There are other *inconveniences* that you might think of, like where are you going to keep it when you're not wearing it? How and how often should you clean it? What about wind noise? How about that loose strap flapping in the breeze? Can you hear OK? Can you be understood talking through a full-face motorcycle helmet? You get the idea.

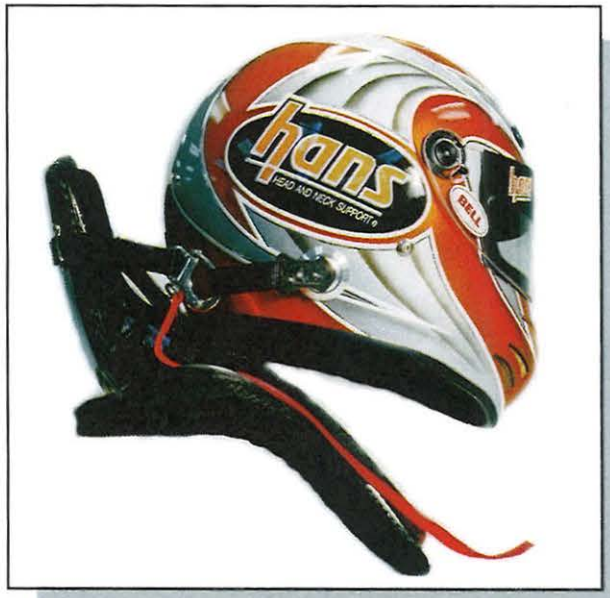


Schutt girl's batter's helmets.

2.1.4 Bulkiness

The total weight of the headgear is of course a critical factor in choosing whether or not to wear a helmet. Depending upon the particular application, the weight could vary from a few ounces to several pounds. In addition to general discomfort, excessive weight leads to neck fatigue. This is probably no more noticeable than in high speed motor racing where the inertial loading (*G forces*) experienced by the wearer can easily quadruple the effective mass of the helmet. In the case of auto racing, the helmet was often tethered to the vehicle or to the driver's torso to minimize lateral loading on the neck during high speed cornering.

More recently, the HANS (Head and Neck Support) device has been adopted by nearly all racing car drivers. This can minimize the inertial (weight related) loading on the neck from the helmet by limiting the extent of head movement in a crash. However it doesn't reduce the weight and *G forces* on the neck during normal driving operations. HANS is discussed in more detail in Chapter 6 under Auto Racing Helmets.



The Head and Neck Support HANS couples the helmet to the driver via the shoulder belts. *Courtesy HANS Performance Products.*

Just as important as total mass is the mass distribution. The most uncomfortable type of headgear is that for which the center of gravity of the helmet is displaced from the center of gravity of the wearer's head. Many so-called "shorty" style helmets formerly worn by many motorcycle police officers, for example, were not *too* heavy but they were *top* heavy. Not only did this tend to be uncomfortable, but it increased the propensity for dynamic instability. That is, it could be readily ejected from the wearer's head during an accident. A heavier full-face style of helmet might actually be more comfortable and more stable since the center of the helmet mass is nearer to that of the head itself.

And too high a weight can influence an athlete's performance too. In Sweden, hockey helmets by law were not permitted to weigh more than a few ounces. It was felt that heavier more protective designs might slow them down. In skiing competitions, the constant movement of the head has also demanded that helmets be lightweight. In bobsledding however, heavy old motorcycle helmets will do just fine.

2.1.5 Thermal Considerations

Nobody likes a helmet that's *too hot*. The fact is that most helmets are made of materials that are excellent thermal insulators. In one advertisement by Dow for its products, its polystyrene is touted as a material used in helmets and refrigerators.

Generally, the heat that one is concerned about is metabolically derived. That is, it's from the head itself. The exposed head deals with this by sweating. Cooling is promoted by evaporation of sweat from the skin's surface. When the head is encased in an insulating structure, this cannot happen.

Most modern auto racing, motorcycle, and equestrian helmets provide very little in the way of cooling for the head (though ventilation is one of the more frequently touted features in helmet advertising). The assumption is that the wearer will be exposed to wind in his face and that will suffice. In fact a motorcyclist will not generate much metabolic heat since he is quite inactive sitting on his vehicle — unless of course he is competing in a race. Even in the most active form of motorcycle racing — motocross, the interior liner will often wick away much of the sweat that is produced and the relatively little ventilation provided through the helmet will often be adequate. In closed cockpit auto racing such as NASCAR, the heat inside the car can be overbearing and auxiliary forced ventilation may have to be provided. Bicyclists, hockey, football, and lacrosse players, on the other hand, generate a lot of their own heat and ventilation of their head is crucial — and not just when they're moving. It has been suggested that modern cycling helmets have become more of nothing (vent openings) than of something (actual helmet).



Impact Racing's Air Draft forced vent full-face racing helmet.

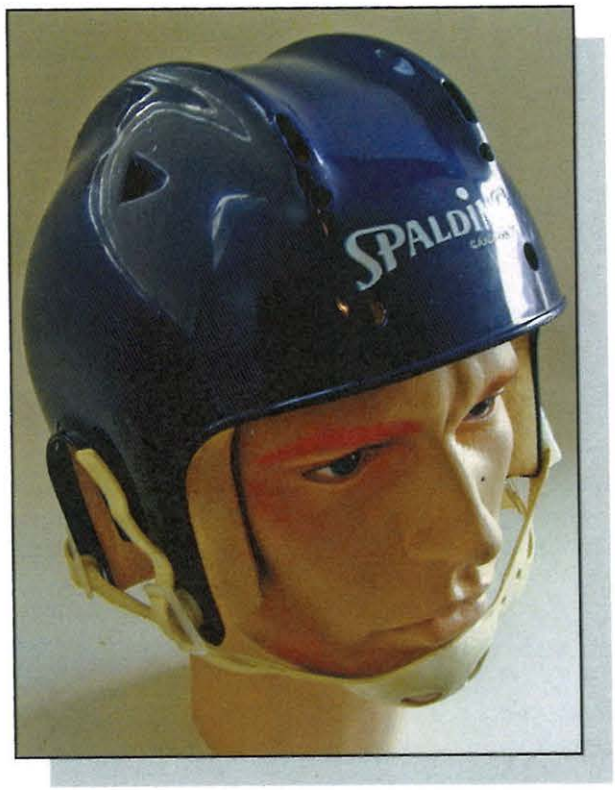
Unlike crash helmets, football helmets typically provide a substantial stand off between the head and the helmet interior. This, plus tiny holes at the top of the shell, has been the means by which football helmets provided for ventilation. This is not terribly effective and, as you may have noticed, football players at the end of their shift often remove their helmets to cool down at the sideline. (Unless they're playing in Green Bay in January, for example, in which case they happily keep them on). Hockey players, on the other hand who change shifts much more frequently, don't have the time for that luxury. When they're sitting on the bench or in the penalty box, it's critical that heat be able to vent from the top of their head while the helmet is still being worn.



The Louis Garneau Ozzy Bicycle helmet.

While all of this is pretty obvious, having one's head too well ventilated can also occur. Vents in bicycle helmets need to be closeable if a wearer, as many do, plans to ride in the winter. Or provisions may need to be made to allow the wearer to put a cap on under the helmet. Having –20 degree air whistling through your helmet while skiing or snowmobiling, is also not a great idea. At the same time, however, many snowboarders generate a lot of that metabolic heat and they *need* to ventilate.

OK, this is all fine and good, and if you pay attention to all these *user requirement* issues, you could have a successful design. BUT will it *work*? That is, will it perform when called upon to protect the wearer's head? Let's face it, when all is said and done, the only reason to wear a helmet is protection so it had better perform.



The Spalding HH-1 hockey helmet co-designed by the author was a commercial failure of the 1970s partly because of insufficient ventilation through the top of the helmet. *Author's collection.*

2.2 Performance Requirements

In modern terms, a sports helmet is simply a device worn on the head to reduce the probability or severity of head injury that would otherwise occur when the wearer's head is struck. That the head be struck for a helmet to work is pretty obvious but head injury can occur without that necessarily happening. For example, many helmets don't cover the face and none protect your chest and impact to either of those parts of the anatomy can create head and brain injury.

What makes helmet designs different is the environment in which specific head gear has to provide protection. As we'll see, motorcycle helmets as well as those for horse riding, hockey, and even bicycling, for example, have many of the same basic performance requirements as, for example, auto racing. They just function in different environments and will differ substantially depending on the specific nature of the threats with which they must deal.

Performance requirements stipulate the nature and level of protection the helmet is expected to provide. These are generally addressed by performance *standards*. And as we'll see later, there is no shortage of organizations that prepare and publish helmet standards. Among these are ANSI, ASTM, BSI, CPSC, CSA, DOT, ECE, FIA, and NOCSAE to list several acronyms.

Depending on the situation, there may be requirements for helmet stability, abrasion resistance, as well as overall stiffness, shell friction, and conspicuity, and so on (that lets

you add any others you can think of). However, historically the three most significant of such requirements are shock attenuation, helmet retention, and penetration resistance. It is these that directly address the threats to the head and the need to keep the helmet in place when required.

In the next few sections we'll talk generally about these performance features. What we'll need to do eventually is try to quantify how much of any of these is adequate. For example, how much impact energy should a helmet be able to attenuate and at what force levels in order to protect one's head in a specific *threat environment* (That sounds SO sinister). In order to do this, we'll need to know more about the kinds of head injuries there are and the mechanisms by which they occur. We'll then need to somehow establish some suitable performance levels and some tests to measure these characteristics. Before going there, let's have this general overview of performance requirements.

2.2.1 Impact Attenuation and Its Relation to Brain Injury

The single most important performance feature, no matter what the application, is the capacity of any helmet to deal with the energy associated with an impact to the head.

Everything else is secondary

Every helmet does its job by providing a barrier between the head and whatever is striking it. There are of course an infinite number of ways the head can be *struck* and it makes no difference whether the head is struck by something or the head strikes something. As an old chap with grey fuzzy hair may have once put it *"It's all relative."* Impact might be due to striking your head on the roadway after falling from your motorcycle or, in hockey, hitting the ice surface after a stiff body check. If you are playing football, striking your helmeted head against that of an opposing player can do it. A race car driver may hit parts of the vehicle interior several times as his car flips down the straightaway. A horse's hoof, a smooth stone launched from a leather sling, are all very different impact threats. The ability to attenuate impact loading is the most crucial part of any helmet design.

The purpose of the helmet *barrier* is, to put it in familiar terms, simply to *cushion* the blow. And in perhaps less familiar words, to absorb the impact energy and to dissipate and distribute the forces that would otherwise occur when this impact occurs.

Distributing the force over a larger area reduces the localized loading on the skull and its propensity to deform inwardly at that point. This in turn reduces the likelihood of skull fracture and brain damage immediately below the impact site. *Reducing* the magnitude of the force reduces the extent to which the head is accelerated away from the impact. This acceleration is associated with a different kind of brain injury mechanism.

The main principles governing helmet design are governed by the laws of physics. There is a fundamental mathematical relationship between linear acceleration, stopping distance, and speed. Given the available thickness of the helmet and how fast the head is moving when it hits something, this relationship determines how quickly your head comes to a stop. For example, if the head strikes an immovable object (read: large tree, cement culvert, front bumper of a bus) at a speed of about 10 miles per hour and the helmet is 1 inch thick, the absolute minimum acceleration of your head that can be achieved with a helmet perfectly designed for this impact, is at least 80Gs. This is as hard as a well thrown punch from Lennox Lewis and you are going to have at least a concussion. At 20 miles per hour, this same helmet but now *perfectly designed for this impact*, will result in a head acceleration of over 300Gs and if it's *your* head, you're dead. Period. To get head acceleration at the 80G level, for this impact you'd need a helmet that is at least 4 inches thick.

Early helmet design tried intuitively to protect against the former mechanism — skull deformation. They typically didn't provide the *thickness* to reduce head acceleration substantially. Only in modern helmets did the latter mechanism, brain deformation, begin to receive attention. To reduce brain deformation you must reduce the head acceleration and for any given impact, the only way to do this is to increase the stopping distance, which is why helmets have become bigger and bigger over the years. Nowadays, even though protection of the skull, and scalp and its integuments (don't you just love that word?) continues to be important, it is the minimization of brain tissue *distortion* that is the principle object of head protection. The way this *distortion* is measured or quantified is a subject that even today generates heated discussions in the biomechanical scientific community.

The other important performance requirements of a helmet are that it should resist penetration by any external object and it should stay in place on your head where it's supposed to be.

2.2.2 Penetration Resistance— How to Avoid Getting Stabbed in the Head

Historically, the ability of a helmet to prevent intrusion by some sharp object can be important. Some racing car drivers (Ayrton Senna for example) have been killed as result of an errant vehicle part piercing their helmet (then their head) during a crash. The Federation Internationale de l'Automobile (FIA,) the group that looks after Formula 1 racing, recently upped the penetration resistance requirements for driver's helmets to levels never before contemplated.

In ice hockey on the other hand, penetration by a skate blade was once thought to be an important consideration — then newer skate designs changed all that. Nevertheless, the size of the holes in the shell reflects a need to insure that sharp and pointy things don't find their way to the wearer's head.

In motorcycle racing, penetration resistance is of a secondary concern. However, in a crash a motorcyclist's head may occasionally encounter an object such as a guard rail support bolt or some other aggressive trackside object — or even part of his or another rider's bike.

In the early days of the modern bicycle helmet, penetration resistance was thought to be an important factor. Later it was considered less important than having a lightweight design.

It's not a factor in most other sporting applications and we won't spend much time talking about it. The fact is this requirement has seldom stemmed from any serious analysis of actual threats but from the early pioneers' feelings that it had to be good for any helmet to have *penetration resistance*. They did not imagine helmets without outer shells.

2.2.3 Retention and Stability — Keeping It Where It's Supposed to Be

This requirement is pretty standard for most types of helmets. It simply acknowledges that any protective headwear is of little value if it doesn't remain where it's supposed to be — properly in place on the wearer's head. This doesn't necessarily refer to the helmet being completely stripped off the wearer's head during an incident. This has resulted in the death of more than one motorcycle racer. If the helmet is displaced somewhat during an event it can expose parts of the head that would otherwise be protected. Dynamic stability of the helmet on the head is an integral part of retention capability and we'll see later how designers try to incorporate it and how it is addressed in certain performance standards.

2.3 Conflicting Requirements — And There Are Always Conflicts.

Invariably, it seems, these sets of requirements are at conflict with one another and improper consideration of each can, at one extreme, lead to a *hot*, heavy, expensive unattractive helmet that provides excellent protection, or, at the other extreme, produce a cool, light, attractive, inexpensive device that offers virtually no protection. In both cases, the design would be a failure, since in one case it would *work* but would not be used and in the second it would be used but not *work*. The optimum clearly therefore lies somewhere between these two extremes.

Restrictions, whether imposed by standards, operational considerations, or consumer attitudes, clearly limit the extent to which the designer can manipulate the various material and geometry alternatives available to him.

One important requirement that hasn't been mentioned relates to the wearer's ability to see (and in some cases to hear) what's going on around him. Restrictions on minimum field of view or hearing level are neither performance nor user requirements as such but in sporting applications are obviously important. A helmet with a limited facial opening or one that covers the ears completely could compromise the athlete's performance and worse, precipitate an accident that would otherwise not have occurred.

Finally, a most important helmet design principle: don't design a feature into a helmet

that could produce an injury.

Cases of children being strangled on playground equipment by the straps of their bicycle helmet have been reported in Canada and Europe. As a consequence, the standard for children's helmets was rewritten to account for that possibility by including a *quick release* feature in the retention system requirements.

In Canada in the 1980s, widespread mandatory adoption of helmet-mounted faceshields in amateur ice hockey precipitated a huge increase in spinal cord injury incidence and severity. Though there was no direct *mechanical* connection between neck injury and the faceguards, the *they can't hurt me now* syndrome led to even more reckless play and the unprotected neck became a victim. Changes to rules regarding hitting from behind as well as a major education program eventually brought the situation back under control.[12]

When improved helmets were introduced in American football, players began spearing opponents with their helmeted head and catastrophic neck injuries occurred. This inappropriate use of the helmet as a weapon was eventually written into the rule book and neck injury through this mechanism has decreased.

As complex as dealing with all of the above conflicts might be, we have not even begun to consider other important issues, such as quality control, distribution, storage, packaging, etc. (And we are not going to consider those issues here either. — Have to leave *something* for you to figure out yourselves!).

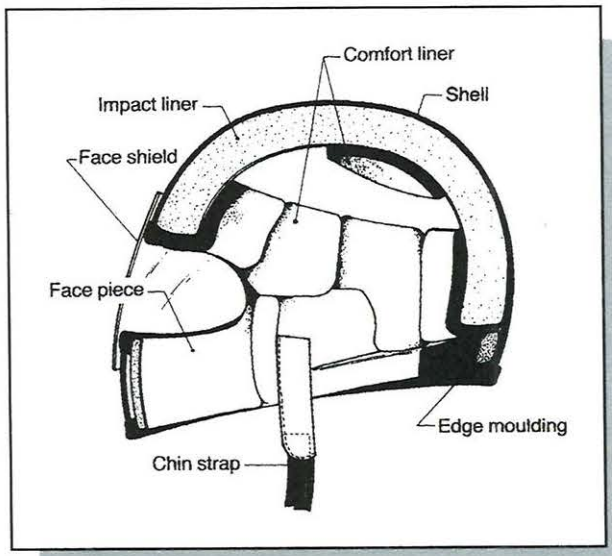
But wait. None of this matters if you don't know how to *make* a helmet, right? So enough of *principles*. Let's talk hardware.

3 Design and Construction

3.1 Shell

A sports helmet can consist of up to four primary elements. These are: the outer shell, an impact energy-absorbing liner, a comfort-fitting system, and a retention system.

A section view of a typical full-face auto/motorcycle racing helmet is shown in this Figure. Athletic and crash helmets all possess the same basic elements, though in different proportions and with different emphases.



Cross Section of Full-Face Auto Racing Helmet.[13]

From a functional point of view, the object of the shell is to provide a hard, smooth outer surface which serves to distribute the impact load over a large area. It also provides a penetration shield against high-speed and/or sharp pointy objects and in addition, serves to protect both the wearer and the underlying liner of the helmet from abrasion with, in the case of *crash* helmets, the road surface. It also provides a surface upon which various graphic designs can be inscribed in some way or another. Having said that, modern cycling and ski helmet design (and some equestrian helmet design too) makes a significant departure from these general rules. Nowadays, the thin outer shell does virtually nothing to withstand penetration or abrasion and it does not help distribute the impact over a larger area. Though it may help contain larger fragments should the helmet be subjected to a massive blow, it is largely decorative. There are two ways by which these *micro* shells are produced. In both cases the shell is vacuum formed and the holes and edges are die-cut. Often, it is simply glued and/or attached with tape in place. For higher end helmets, the shell is formed from polycarbonate which is *co-molded* to the liner in the liner mold.

Common material alternatives for a *functional* outer shell are fiber reinforced plastic (FRP) composites and thermoplastics.



This cartoon reflected the importance helmet designers put on the helmet shell back in the early 1950s and during the rest of the twentieth century.[11].

3.1.1 Fiber-reinforced plastic.

Some modern high performance auto and motorcycle helmet shells are made of composite materials, most commonly woven fiberglass cloth bonded with polyester resin. There are various catalysts, promoters, and sometimes plasticizers in the resin to make it cure into a solid, and there can be a variety of fillers and/or modifiers in the resin. Different types and weaves of fiberglass cloth can be employed as can other fabrics such as graphite fiber, nylon, polyester, and others with names like Kevlar® (a fabric made from polyaramide fibers), Spectra® and Dyneema® (both polyethylene fiber material). Also, other resins can be substituted for polyester such as epoxy or vinyl ester.

Modern FRP helmet shells are usually compression molded, whereas in the past a hand lay-up process was more commonly used. In pressure molding, most often a bag is inflated inside the mold to compress the composite and to distribute the resin. The process, sometimes in conjunction with so-called *chopped strand* techniques, produces a relatively homogeneous structure of fibers imbedded in a plastic matrix. The hand lay-up process, which also may employ high pressure molding techniques, uses a series of several (usually die-cut) small sheets of fabric soaked in resin (or pre-impregnated). These sheets overlap at their edges in the female mold. Following curing of the resin, this process produces a thick, strong shell with thicker (reinforcing) ridges at those overlapping zones. In either case, when cured, the shell is then trimmed at the edges and the eyeport is cut out.

In the 1950s and 1960s, fiberglass was the sexiest material around. If they could make a Corvette from it, why not helmets. Then with the advent of *bullet proof* vests and other soft body armor, came Kevlar (and competing fibers) with tremendous tensile strength for its size and weight. Its ability to resist penetration by high velocity projectiles made it a candidate for high performance crash helmets. However, when molded into a solid helmet shell, the benefits over fiberglass were not that evident. Same thing now is happening with *carbon fiber*. Racing car bodies are made from the stuff so it should be good for helmets right? Well it's a lot more expensive than fiber glass or Kevlar and again the benefits are not that clear for this particular application. Nevertheless, the most expensive and exotic helmets around now have shells made, at least partially, from carbon fiber fabric. It is now the sexiest material around.



The shell of this HJC off-road motorcycle helmet is fabricated entirely from layers of carbon fiber cloth. The AC-X3 features a true full shell application carbon fiber. With a dual density liner EPS liner and removable comfort liner, this unit weighs only 1350 grams.

3.1.2 Thermoplastics.

Thermoplastic shells are, for large scale production, cheaper to produce as they can be readily injection-molded. This process entails no more than melting the plastic, injecting it into a steel mold and allowing it to cool and solidify in the mold. When solid, the finish part is simply ejected from the mold. Parts made this way usually require very little in the way of hand finishing operations. Materials typically used are polycarbonate, Acrylonitrile Butadiene Styrene ABS, and most recently polycarbonate/ABS alloys. Other thermoplastics such as high density polyethylene are used in certain sports helmet applications, but not for crash helmet shells.

Polycarbonate was discovered by H. Schnell at Bayer AG, Germany in 1953, and by D. W. Fox at General Electric Company, USA, working independently. In the late 1950s polycarbonate began to be used in commercial applications. In 1957 came the Sputnik and polycarbonate, the *Space Age Plastic*. Polycarbonate was sold by GE under the brand name Lexan® and it found uses throughout the world from street lights to automotive headlights. Its biggest feature is that it is *tough*. Not the easiest plastic to form into helmet shells, when done properly it has performed admirably over the years. It also looks good with a nice glossy finish.

ABS is also an ideal material for helmet shells. ABS, (the plastic most often used today in appliance housings, pipe, telephone headsets, and luggage) owes its origins to research work emanating from the World War II-era program aimed at producing large quantities of synthetic rubber. It does not have the same penetration resistance as polycarbonate and it tends to be a bit less lustrous but it's generally easier to work with and not as expensive. Its toughness is the result of microscopic rubber (polybutadiene) particles uniformly distributed in the styrene acrilonitrile matrix.

For the same volume of material, thermoplastics are somewhat lighter than the FRP materials, however, they also tend to be less rigid. Furthermore, they can be susceptible to stress concentrations set up, for example, around rivet holes and in these areas, could be inherently weak. Shells made this way require very little in the way of hand operations and may not even need to be painted. Football and hockey helmets are examples where injection molded polycarbonate or high density polyethylene (HDPE) are often the materials of choice.

Thermoplastic helmet shells can also be *vacuum formed*. What this means is that a sheet of polycarbonate or some other thermoplastic is heated until it starts to become *droopy*. It is then laid over a metal die in the shape of the intended part. The sheet is then sucked onto the mold creating a duplicate shape of the mold. The part, when cooled, is trimmed, holes are drilled/punched or cut as required, and it's done. The thin *micro-shell* of the modern bicycle helmet is made this way from the same plastic used to make milk jugs, PET (you really don't need to know what those letters stand for) or, in some cases, from polycarbonate.

The functional outer shell of the first modern bike helmet the Bell Biker, was vacuum formed but from a substantially thicker sheet polycarbonate.

One final feature about thermoplastics relative to FRPs, is that they can be brittle. This particular behavior may be amplified under certain environmental conditions (e.g., extreme cold). FRPs on the other hand, tend to crush, delaminate, or tear rather than fracture on impact and, if properly molded, tend to be less sensitive to environmental conditions.

3.2 Impact Liner

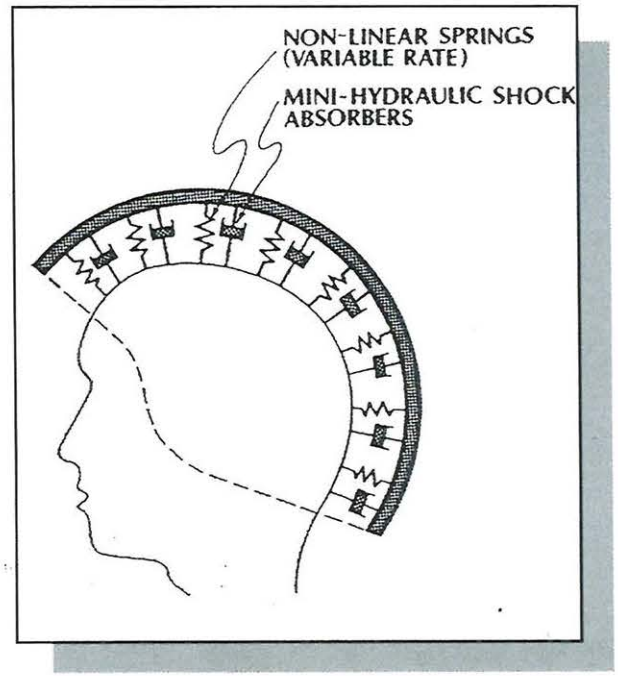
Interior to the shell is the liner of the helmet. It is this element, through its deformation and in some cases partial destruction that is largely responsible for absorbing the energy of impact.

In order to perform its function effectively, the liner material must deform at stress levels below that which would cause head injury. Its strength should be largely insensitive to impact velocity and, to maximize net energy absorption, it should have slow (or no) rebound characteristics. These requirements dictate that the liner should have a well-defined, relatively constant, low crushing/yield strength and be relatively strain-rate insensitive.

As you've seen from the history section, there are two basic types of foams used in helmet liner applications, resilient and crushable. Resilient liners are employed in repetitive athletic applications. Crushable materials are used in crash helmets for that *one-time* accidental impact. A third type, the crushable resilient liner (a combination of the two basic properties), has also found limited applications as discussed later.

Regardless of the type of material used, it can be too strong or too weak from a head protection viewpoint. Too strong (imagine your helmet made of cement) and high forces are developed before the material crushed — and you die. Too weak (a nice down filled liner inside the shell) and whatever is hitting your head blasts right through the padding — and, again, you die.

As important a consideration as this may be, the recovery or rebound characteristics are what determine the overall energy absorption. And the degree of recovery determines the extent to which the material will be available for subsequent impacts.



The liner as seen by the helmet designer.[11].

3.2.1 Crushable Liner.

Without question, the most popular, perhaps the only *crushable* liner used in crash helmets today, is made of expanded polystyrene bead (EPSB) foam. The EPSB liners are produced by introducing a known amount of unexpanded polystyrene beads into a closed mould and injecting steam. This causes the individual beads to expand and to adhere to each other. The resulting liner is a relatively stiff homogeneous structure possessing desirable stress/strain properties. The one governing factor that determines the crushing properties of the material, aside from the exact bead chemistry itself, is the bulk density of the molded part. This can be controlled quite accurately by controlling the degree of pre-expansion before the beads are inserted into the mold. It is not uncommon nowadays to find bicycle and some motorcycle helmet liners in which the EPS liner assembly is made up of components of different densities. This is often done to optimize the protection at different sites on the helmet and to accommodate ventilation openings.

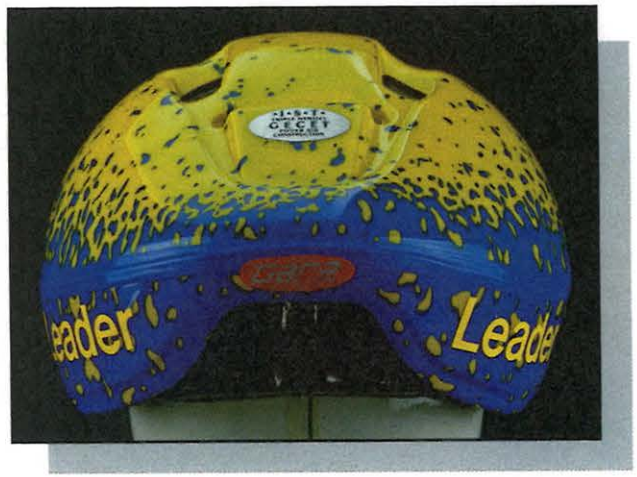
A popular variation on ESPB foams in bicycle helmets was GECET®. A proprietary blend of polystyrene and polyphenylene oxide, this particular material has greater structural integrity than pure ESPB foam but retains the same desirable crushing characteristics. In recent years however, the structural characteristics of bicycle helmets have been such that this material is no longer used and plain old ESPB foam still reigns.

3.2.2 Resilient Liner.

A perfect resilient liner system is one that deforms upon impact, does not rebound but, before the next blow to the head occurs, recovers fully its shape and its physical properties. Many rubber-like types of foam have this general characteristic and have appeared in many different football and hockey-like helmets over the years. Pliable polyurethane or vinyl nitrile foam is the basic material of modern choice, though some helmets continue to use polyethylene and polypropylene foams. Over the years, some designers have gone to great lengths to develop energy-absorbing systems exhibiting these properties by combining various fluid and gas filled bladder structures with foam materials.



The modern Arai GP5 auto racing helmet with the *PED* aero add-ons, employs five different densities of EPS in its liner to fine tune the impact response at different sites on the helmet.



The Canadian-made Leader bicycle helmet of the late 1980s was one of the first to employ GECET foams of 3 different densities to optimize impact performance. *Photographed by Stephen Fenn.*

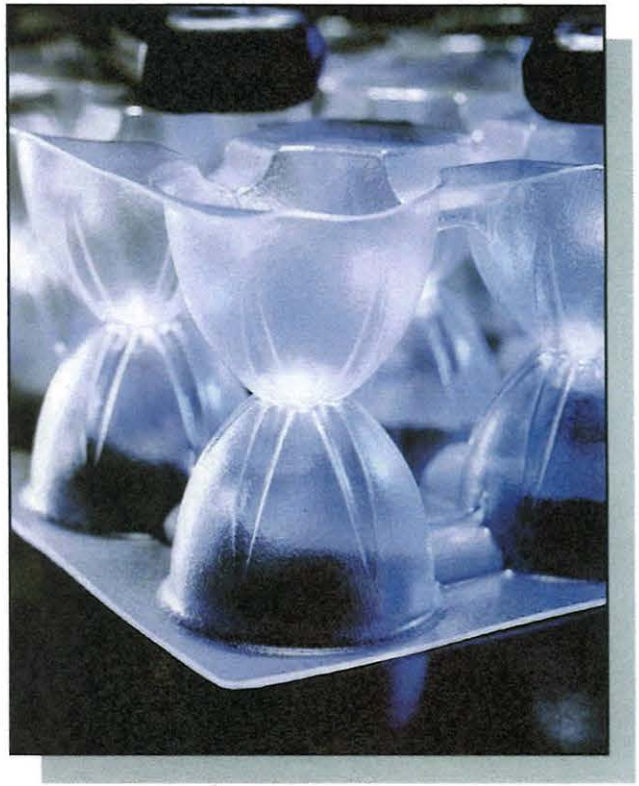
3.2.3 Crushable-Resilient Liner.

In an effort to combine the characteristics of both types of materials, some manufacturers have employed expanded polypropylene bead (EPPB) foams. The manufacturing process (and the appearance) is not unlike that of EPS liners but the resultant product has interestingly different properties. In particular, this foam has certain *recoverability*. Following an impact it will regain most of its structural properties. Such a liner is often thought to be suitable in some racing accident situations where the wearer may have his head exposed to multiple impacts during the course of his accident. It has also found application where multiple crashes during the life of the helmet is not unexpected such, for example, as in skateboarding or BMX bicycling. It is even used in some newer hockey and football helmet designs. The downside is that as the material recovers during head contact, it could possibly increase the effective impact velocity of the head and increase the chance of head injury compared to a material that stays crushed.

Semi-rigid polyurethane foam continues to find applications in this area. Many bicycle helmets, intended primarily for BMX or mountain bike riding, are made almost entirely of this material. This is the same material that is used, for example, in padded automobile dashboards. Whatever the part, it is produced by introducing into a closed mold two fluid components which, when mixed, get hot (exothermic reaction) and begin to foam and in a short time, fill the mold. When cooled, the part is the shape of the mold interior, is full of bubbles and somewhat pliable. When removed from the mold a smooth or decorative *skin* envelops the part. The degree of *pliability* depends on the specific choice of chemical composition and the mixture ratio. (*Rigid* polyurethane foam is used this way to make a lot of furniture nowadays.)

There are, as it seems there have always been, contenders to the crushable-resilient energy-absorbing materials currently used in helmets. One such modern alternative is Skydex®. Picture a bunch of plastic egg cartons stacked on top of each other. Now imagine them to be very small. Skydex is custom made and the size and spacing of the *egg cup* depressions can be varied as can the thickness of the plastic material itself. The result is a highly *tunable* energy-absorbing material that has already found application in some US navy helmets and in the Schutt DNA football helmet.

Another possible contender is called Brock®. Currently being considered to absorb energy under synthetic turf playing fields, it's a lot like EPPB foam — without the E. Rather than being expanded and thereby having no gaps between them, individual polypropylene beads are essentially glued together. The PP beads remain more or less spherical with gaps between through which air can pass. Picture a jar full of marbles. That's how these beads are stacked on one another. Again, excellent energy-absorbing capabilities that can be tuned to a specific application. And through which air can pass.[14]



Skydex® energy-absorbing structure.
Photo courtesy Schutt Sports Inc.

3.3 Comfort/Fitting System

The overall size and shape of any helmet is governed by the shape of the shell and the interior impact liner. The fit is dictated by the *comfort padding* or adjusters which are secured to the interior of the helmet.

The object of this padding assembly is twofold. It must of course provide inherent comfort and it is also responsible for the accommodation of different head sizes and shapes. The comfort padding material must therefore be elastic, soft and strong.

The requirements of the comfort padding dictate that relatively soft but durable foam be used. The thickness may vary from 0.125 to 0.5 inches. Polyester, polyether foams covered with a brushed nylon fabric are generally considered suitable. Helmets intended for competition may also employ a removable cotton inner liner that may be laundered.

Modern (i.e. post 1975) cycling helmets have typically used small polyester foam pads that can be strategically placed inside the helmet by the wearer to accommodate different head shapes and sizes. The sticky backing on these pads, or on the Velcro® stuck to liner, often didn't last beyond the first year or two of helmet use. More recently this approach has given way to adjustable suspension designs not unlike that used 30 years ago by Bailen in its inaugural bicycle helmet design.

Hockey helmets historically have been the only design that employs a multi-piece or split shell to accommodate a wide range of sizes. Today the shells still are typically adjustable from front to back but not in width and usually no sizing pads are provided to make up the difference.



An early Bailen bicycle helmet showing the inner adjustment system adapted from the common construction hard hat. *Author's collection.*

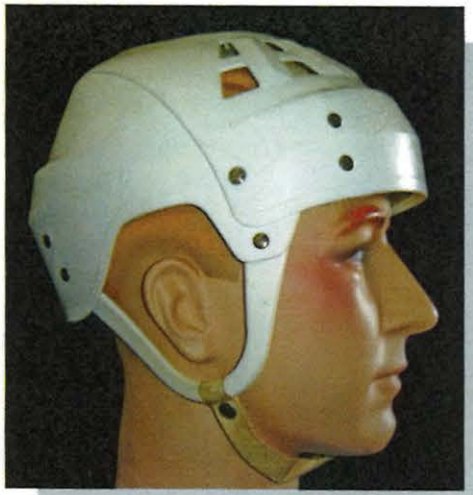
Newer bicycling, equestrian and lacrosse helmets, and even the occasional hockey helmet, use an adjustment device that can tighten the helmet on the head.



This old-timer hockey helmet had plenty of adjustability via the lace on top and lots of elasticized straps. *Author's collection.*



This 1950s style hockey helmet comprised three separate plastic pieces, a few nuts and bolts, and lots of holes to accommodate a wide range of shapes and sizes, not an uncommon design at the time. *Photographed by Stephen Fenn.*



Jofa pioneered the hinged shell design in the early 1960s and retained the concept throughout most of its many model variations. *Author's collection.*

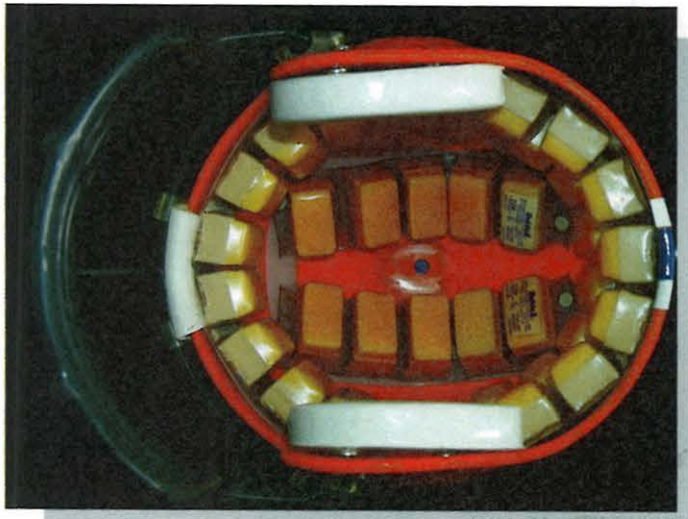


A novel design was employed by the Nestor Johnson Company in its very early one-piece shell hockey helmet. Here an inflatable rubber liner could be *blown up* via the wearer's own mouth until it felt comfortable, c. 1960. *Photographed by Stephen Fenn.*



The most popular hockey helmet of its time, the 1960s, the CCM Pro-Guard had two sections that bolted together in a way that allowed some size adjustment. *Author's collection.*

This Riddell PAC-4 football helmet from 1974 had a series of interconnecting foam-filled cells. To improve fit, these could be inflated via a valve in the shell using the same compressed air source as used to inflate the football itself. Thinner or thicker cheek pads could also be snapped in. *Author's collection.*



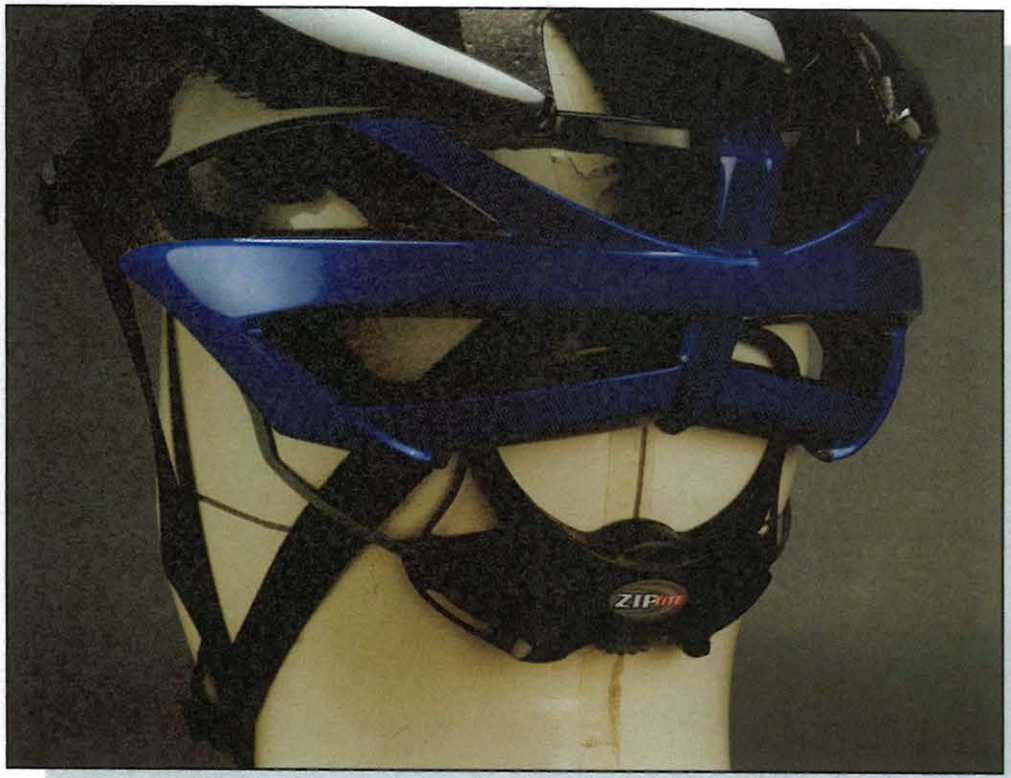
3.4 Retention System

Keeping the helmet on the head can be viewed in the same light as keeping any other piece of apparel attached to your body, your shoes, your pants, etc. In fact the concepts of shoelaces and belt buckles dominated early design.



A modern Nike-Bauer hockey helmet with an *occipital lock* to assist fitting of helmet.

The trick in retention system design, however, is not simply to keep the helmet in place during normal wear, but to do so in a situation where a head impact has occurred or is about to occur. After the skier has fallen and is tumbling toward the trees, when the motorcycle rams the car's passenger door after the oncoming car turned left in front of it, as the jockey is tossed from his mount but before he hits the ground, after the hockey player takes a shot in the head from someone's elbow but before he then strikes his head on the ice surface, are examples of where *dynamic stability* of the helmet retention system is required. Simply put, the retention system has to keep the helmet precisely where it is supposed to be for its intended application.



A modern bicycle helmet marketed by Trek Bicycle Corporation with a rotary adjuster at the rear of the helmet. *Photographed by Stephen Fenn.*

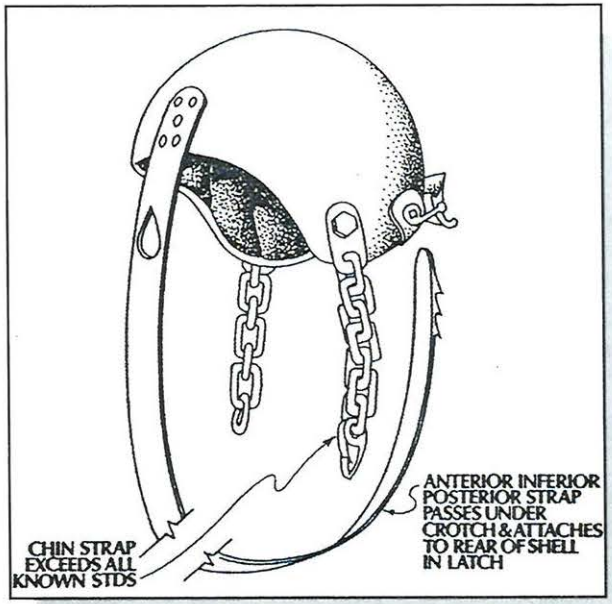


It worked for leather shoes so why not for a leather helmet? This old-timer leather lacrosse helmet was attached to the head by laces at the back. *Author's collection.*

But before you go on reading, it's probably safe to say that of all the variations that could occur in helmet design, the retention system has had the richest history. Variations on various themes have been going on for nearly 100 years and, frankly, unless you're really into the subject, you might want to skip the next few pages.



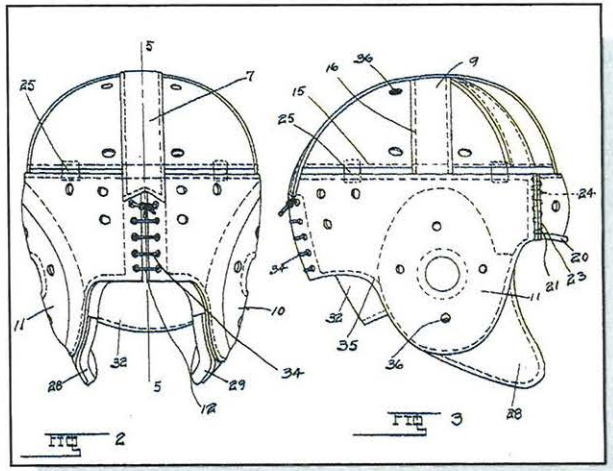
A belt will keep your trousers on so why not to keep your helmet on, as with this early Italian AGV pudding basin? *Author's collection.*



The helmet as seen by the retention system designer.[11].

This issue has tormented helmet designers for years. Back in 1925, an inventor by the name of Goldsmith was granted a patent for a football helmet based solely on the claim that it needed no chin strap.

Many years later a French producer of motorcycle helmets GPA, marketed a helmet that had no chin strap but fastened by a *clam shell* arrangement under the chin. This design was so popular, that the Europeans had to rewrite the retention system test methods in their standards to consider, for the first time, that motorcycle or auto racing helmets might *not* have a chin strap as we know it. Their standards have been so written ever since even though that particular design has gone the way of the penny farthing bicycle. Niki Lauda was one of the top Formula 1 drivers who wore the GPA helmet shown here with this feature.

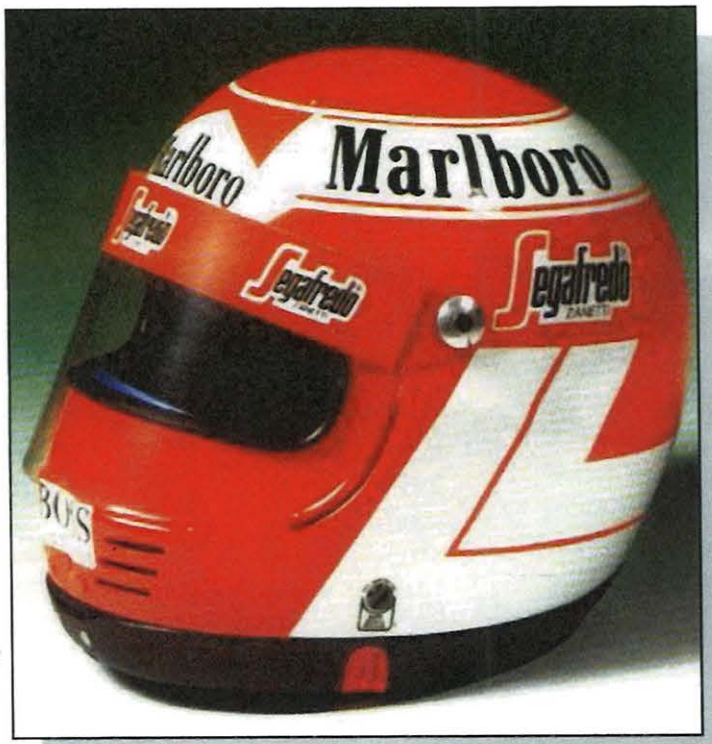


Patent drawings from Goldsmith's *chin-strap-less* helmet. (US patent 1522952).

Every helmet retention system is usually made up basically of four *subassemblies*: the chin straps, hardware to attach the chin straps to the rest of the helmet, a fastening device and some means to adjust the straps under the wearer's chin. There may also be interior fittings or padding in the helmet designed specifically to help keep the helmet in place and there may be related comfort features as well.

Usually, the chin strap assembly is a major element of the retention system. In auto and motorcycle racing, it is as simple as two lengths of flexible material attached with metal hardware to the inside of the shell and some form of buckle at the strap ends. The strap itself must be sufficiently flexible to permit fastening and adjustment, yet strong enough to insure that in an impact situation, it does not break. In addition, it must be sufficiently inelastic to insure that it does not stretch unduly, thereby allowing the helmet to shift on the wearer's head even though properly fastened. It must also be reasonably soft so as to not cause irritation of the wearer's skin. These requirements basically dictate the use of a strong fabric. For most applications, nylon weaves as well as polypropylene have been found suitable.

Most often, at least for crash helmets, the strap sections are attached to each side of the helmet shell by way of a metal or plastic strap hanger which is riveted to the shell –but, as illustrated in Figure 68, not always. Other ways of attaching the hanger have involved rather intricate interior moldings on thermoplastic shells to accommodate the hardware.



Earlier designs such as shown here on an early Everoak motorcycle helmet employed a different approach. The straps themselves were simply sewn onto the neck skirt surrounding the periphery of the shell. Fastening was accomplished with the *fold-over* snap fastener, the adjustment being achieved with the lower strap hardware.

Releasing this GPA helmet from the driver's head was achieved by pushing the red buttons on both sides of the helmet. This opened the bottom (darker) section in a clam shell fashion. This particular helmet was worn by three times Formula 1 World Champion Niki Lauda in 1984. *Photo courtesy Autosport-Net.*



Typical cadmium plated steel strap hanger riveted to the helmet shell on this motorcycle helmet.



Strap riveted directly to the shell on this bicycle helmet — not a good practice.

Bicycle and ski helmets are a different matter. Firstly, they typically don't come down low enough over the ears to facilitate a simple strap arrangement. The first modern bicycle helmet retention systems did have an outer shell and borrowed the Y harness concept from police-style motorcycle helmets. Later, with the disappearance of a strong shell to which strap hardware could be attached a little ingenuity had to be employed.

Some designs threaded the strap material through the liner and over top of the shell as illustrated below. Others kept the strap material completely between the shell and liner.

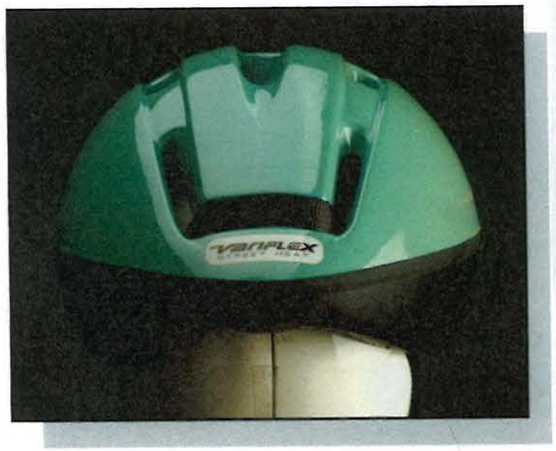


Retention straps of an early Everoak helmet.



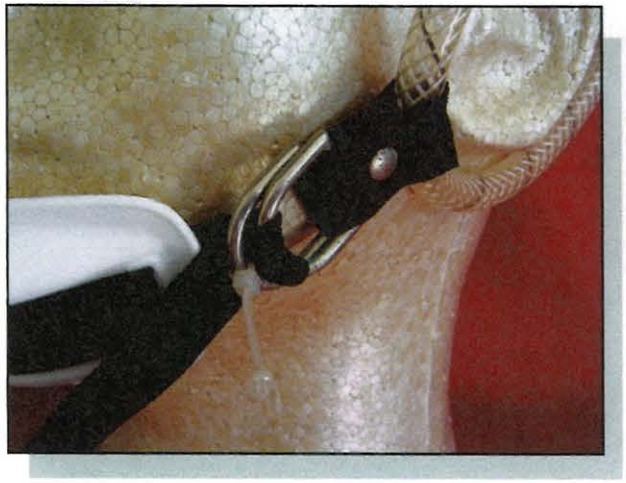


The Variflex Street Heat. The continuous chin strap passes through the shell at the front and at the back of the helmet. *Photographed by Stephen Fenn.*

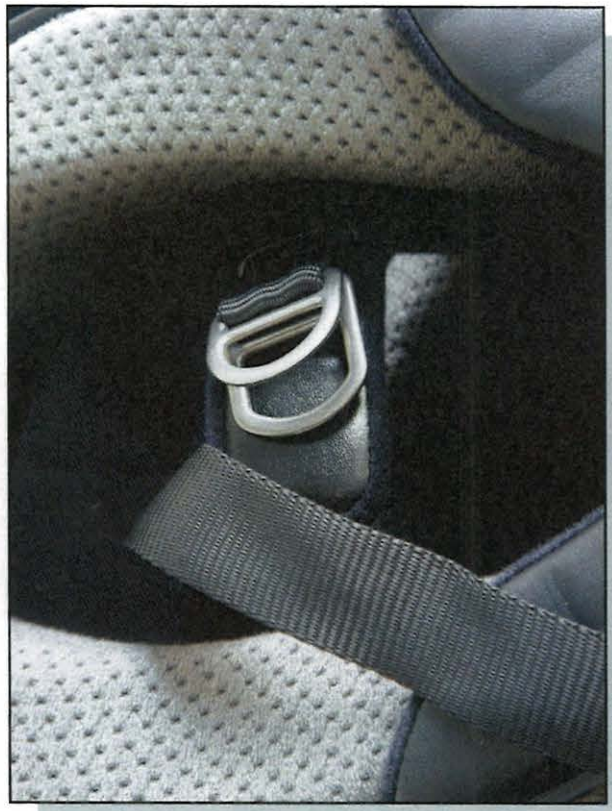


Regardless of how the two sections of strap are attached to the helmet, clearly there must be a good way to attach them together. In this regard, the so called *double D ring* has been the most effective fastening device ever invented and it continues in modified forms to appear on many of today's helmet designs. The shape of the two rings resembled a capital D hence the name.

Recent design changes have produced rings that are clearly no longer Ds, in fact as seen below, the two are not even the same shape — but the name sticks. In any case, if you've ever used one you know it can be a hassle to thread the strap through the rings and even more difficult to unthread it when you want the helmet off.



A Skid Lid bicycle helmet of the late 1970s with several components of a classical retention system including the true D rings, a molded plastic chin cup, and a factory installed quick release tab. *Author's collection.*



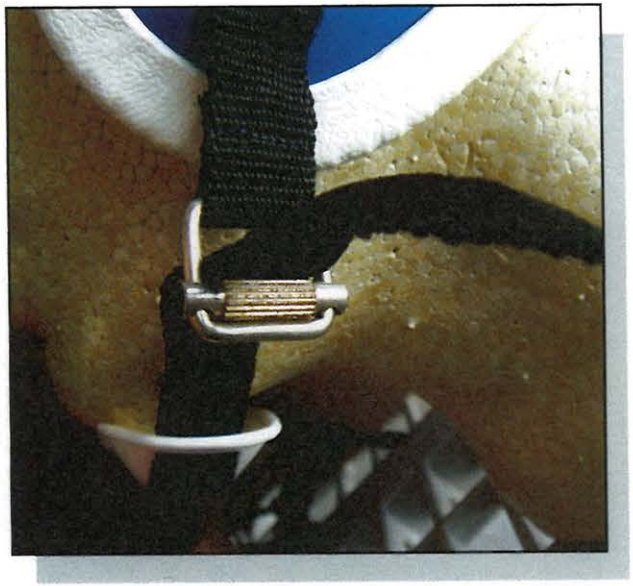
Modern D rings. They are of different shapes from each other, no longer look like simple D's and are flattened to improve grip on the fabric.

Many attempts have been made to supplant the double D ring design, including the *knurled bar* approach shown here. Both the D ring and the knurled bar design require the user to *cinch* the straps tightly enough to prevent the strap from threading back through the buckle. This also insures that the straps are tightly fastened under the chin.



A typical double D ring buckle. Some manufacturers have installed release tabs such as shown here to help disengage the rings and these do work quite well — to a point. Pulling up on the red tab is meant to provide a simple means to release the buckle.

Some manufacturers have tried to come to the rescue by installing more convenient fasteners designed like miniature seat belt buckles. These are in fact more convenient but for many years did not meet the necessary performance levels.





A knurled bar retention buckle as used on an early ski helmet.

Recently, similar miniature buckle assemblies have found favor amongst cycling helmets. The lower performance requirements of these helmets have allowed the use of what are no more than common plastic luggage buckles to become widely accepted. These types of buckles are easier to use than D-rings but may not provide the same level of retention since the straps are not typically *cinched up* like the D-ring or knurled bar type.

When the modern bike helmet was first being developed back in 1975, designers wrestled for years to come up with a buckle system that was lightweight, convenient, durable, etc., and they experienced considerable difficulties.



A typical non-certified miniature seatbelt-like buckle.

A crucial part of a motorcycle helmet retention system is provided in the form of the *neck roll*. By cupping under the back of the head, the neck roll or neck curtain, assists in retaining the helmet on the wearer's head in an accident situation.



A modern bicycle helmet buckle. This particular design features the clever *Pinchguard* to prevent that painful little pinch under the chin that anyone who has worn a bicycle helmet knows about.

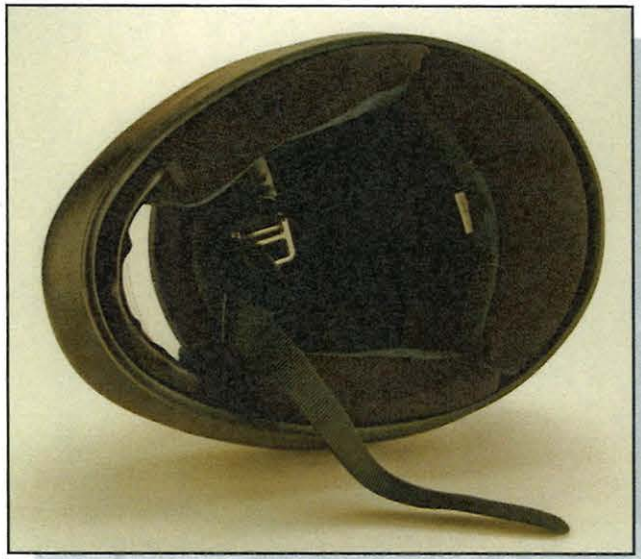


A complex mass of buckle and straps that was ugly, uncomfortable, and difficult to use properly on this bike helmet from the early 1980s.

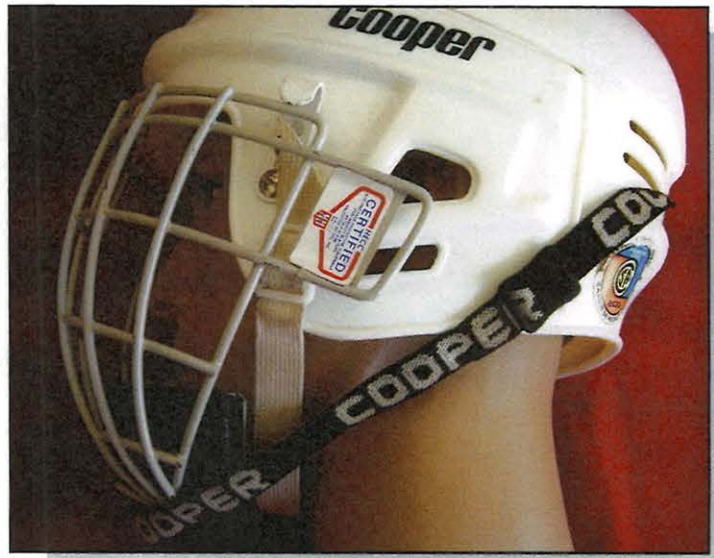
Athletic helmets such as hockey, football and lacrosse, have different, less demanding design requirements than crash helmets. All have the common feature of having exterior snaps by which the chin strap can be easily removed. In the case of hockey helmets there is also the poorly founded belief that there may be occasions during game play when the helmet *should* release from the wearer's head. This requirement is supported by contemporary performance standards which stipulate that if the force on the chin strap exceeds a certain level, it should disengage.

In amateur hockey, the use of faceguards of one kind or another can actually improve the overall retention capability of the helmet. However in professional hockey, face protection is not typically worn and simple chin straps, most often very loosely fastened under the chin, are ineffective in keeping the helmet in place.

When used with a full wire cage facemask, hockey and lacrosse helmet retention systems are very effective.



The use of compliant interior padding material to produce a roll-neck can be seen in this bottom view of a typical full-face motorcycle/auto racing helmet.



This Cooper 2500 hockey helmet uses the padded chin cup and restraining straps of the wire cage to supplement the under-the-chin strap producing a very effective retention system *Author's collection.*

Football helmets interestingly have no published retention system performance requirements. However current designs have proven to be quite successful and maybe that's why no specifications as such were needed. Modern designs use a Y-type harness with a reinforced fabric chin cup. The straps are attached at two places on each side of the helmet. When adjusted properly, this is a very stable system and it is unusual for a football helmet to be inadvertently ejected during use. If it is, it is more often than not because one or more of the snaps was not fastened. Note the length of the straps beyond the snap fastener. This is so the wearer can easily grab the excess strap to facilitate quick release.

But innovation could never have occurred at all if there had not been developed some objective way to determine a helmet's capacity to protect the head, i.e. some way to test it and some measure to judge its capabilities. This is the domain of the biomechanical engineer and the world of helmet standards and is discussed in the next two chapters. First we need to understand something of the mechanical nature of the head injuries we're trying to prevent. The field that tries to explain and understand these phenomena is called the biomechanics of head trauma.



This modern Riddell Revolution football helmet, designed with assistance from the author, employs the classic Y harness with a slight variation. The shell has a simple notch along the lower edge to help keep the lower strap in position.

4. Biomechanics of Head Trauma

Think of your head as an odd shaped container covered with a thick rubbery skin and filled with warm Jell-O®. The Jell-O is not entirely consistent in density and strength but is more or less so. The inside of the container, your skull, is not smooth everywhere and in some places is quite jagged. Your brain, the warm Jell-O is actually contained within a membrane, called the dura, much the same as the membrane an egg is within, inside its shell. That's your head from a *biomechanical* perspective. In order for it to be injured some component of it must be damaged. Like the structural failure of any inanimate object, injuries to any part of the head are nearly always caused by excessive movement of one part relative to another. For example:

A scalp laceration is the result of a mechanical action (cutting or tearing) that separates formerly contiguous pieces of scalp. A lacerated scalp though perhaps messy, is not usually life threatening.

A skull fracture can occur when the skull bone bends more than it is capable of doing without breaking.

Injury to the brain can occur if any part of it is distorted, stretched, or compressed, or if it is torn away from the interior of the skull. A subdural hematoma, for example, is a collection of blood near the surface of the brain caused by the rupture of blood vessels that have been stretched too much. An impact to the head can cause the skull to deform and, even if it does not fracture, the underlying brain tissue can be injured as it distorts under the influence of the deforming skull.

Even if the skull does not bend significantly, but the head as a whole is caused to move violently, distortion of the brain within the skull will occur. This typically leads to generalized diffuse injury such as concussion and, in the extreme, coma.

Separating, bending, and stretching are merely descriptors of somewhat different kinds of movement. By reducing the amount of relative movement between parts of the head, the probability and/or severity of injury can be reduced. This is accomplished with a helmet by, as previously stated, reducing the force on the head that would otherwise be produced on impact, and by distributing the blow over a greater area than would otherwise be the case.

The field of science trying to understand the mechanical characteristics of head impact and how it relates to these kinds of injuries has become broadly known as the *Biomechanics of Head Trauma.*

4.1 Skull Fracture Mechanisms

OK, if you really, truly want to understand the detailed way by which the skull can be fractured you need to read some stuff[15] much heavier than what you'll see here — or go to medical school. This is a very simple *biomechanical* version appropriate to helmet issues only.

The skull is the oblong container in which your brain resides. It is essentially a closed box except for a large hole at the bottom through which your spinal cord passes where it attaches to your brain. Physicians call this opening the *foramen magnum.* (Translation – *large hole).* Attached to the skull are the many bones of the face and of the neck.

A fracture of the skull, by itself, is not really all that serious, less serious than say a fractured leg. However, the circumstances that produce a skull fracture, certainly in the cases of adults, also nearly always produce a brain injury, an injury of much more concern than a simple broken bone. The fracture can traverse and sever an important blood vessel and thereby compromise blood flow in the brain — bad news.

Without overstating the obvious, the skull gets fractured, i.e. it breaks, when it is deformed too much. There are generally three kinds of fractures.

Linear non-depressed. To the non-medical profession this would be called a

crack. More or less straight, a linear fracture can however deviate from a straight line.

Depressed – i.e. pushed in.

Comminuted – the bone has been fragmented or shattered.

The differences between the last two are subtle. If the skull fracture is depressed its almost always going to be fragmented, i.e. comminuted. But, like the shell of a hard boiled egg that you've just hit with the back of a spoon, it could be comminuted without being depressed (much).

The regions of the skull are named after the bone groups that make it up. The forehead region has the really easy name to remember — the frontal. The back of the head is the occipital region. The left and right lower sides are the temporal regions and the upper are the parietal regions. (Someone once suggested that if the medical profession can agree to call the bone at the front the *front*al bone, wouldn't it be easier for everyone to call the others the *back*al, the *side*al, the *top*al bones). The floor or base of the skull is called the, uh, base. The bones or regions of the skull are not of equal strength, being weakest in the temporal region just behind and above the eyes. The skull is strongest at the front and the back of the head.

There are two primary mechanisms of skull fracture, and another that is less so. The first is simply direct, localized loading of the skull. If, for example — and we certainly don't wish this upon you — you get bashed hard enough on the head with the rounded end of a ball peen hammer, the skull will crush and collapse directly under the hammer. The bone will fragment and pieces may lacerate the dura and be driven into the underlying brain. That's not good obviously. And that's what a helmet will prevent from happening.

The second mechanism involves gross distortion of the skull and is more associated with impacts to flat or yielding surfaces. A blow to the strong stiff frontal region for example causes the entire skull to bulge outwards across its width. This stresses bone in the temporal regions and fractures may occur there. These cracks may then propagate and branch off to other weak or highly stressed areas of the skull. A flat blow to the side (i.e. the temporo-parietal region) of the head on the other hand has a different effect. Because of the stiffness of the frontal and occipital regions, most of the skull deformation would occur under the impacting surface, flattening the skull beneath it. Cracks within that region may then be initiated and may propagate down to and along the base of the skull as well as up into the parietal regions. The brain may be injured in these cases (among other reasons which we'll come to) by changes in volume of the space the brain occupies. High and/or low pressure transients occur while the skull is deforming which also disrupt nerve tissue throughout the brain. A good helmet will prevent this by maintaining the proper shape and size of the skull when impact occurs. This is where the *load distribution* part of helmet design comes in.

There are other fracture processes that involve the *base* of the skull. Obviously one cannot impact the base of the skull directly but it can be fractured from indirect loading in several possible ways.

One way is from direct loading to the top of the head through a *compliant* surface like a helmet, where the head is driven down onto the top of the neck with such violence that the neck essentially punches its way up through the bottom of the skull. This is quite rare and it is more likely in these cases, for the neck itself to collapse and fracture.

A different mechanism is where the person's body is rapidly brought to a stop and the head tries to keep going. In this process the head can be torn from the top of the neck by fracturing at the base of the skull. Helmet weight could be a contributing factor in these situations.

The third mechanism is most interesting in an era when full-face helmet designs have become so common. If you get struck from the front hard enough on your unprotected jaw, the jaw will break. If, on the other hand your jaw is protected by a stiff, strong, well padded surface, the force will be nicely distributed over the jaw bone and instead of breaking it, it will tend to be driven backwards. If it's driven backwards hard enough, it can break or punch through the base of the skull where the jaw articulates (rotates) just below the ears. A fracture here will tend to propagate across the floor of the skull and the trauma to the brain and brain stem is often fatal. To guard against this fairly rare occurrence, the faceguard portion of the helmet needs to be as far away from the chin as is reasonably possible and padded in a way as to reduce as much as possible the force that would tend to drive the jaw backwards. Alternatively it could be designed to collapse upon impact so as to localize the loading on the jaw and

to produce jaw fracture rather than a fatal basilar skull fracture.

So, helmets protect against skull deformation and fracture, and the associated brain injury, by providing a strong stiff structure that *distributes* force over a larger area and thereby helps to retain the normal shape of the skull. This is probably the easier part of helmet design principles to understand. What may not be so easy to grasp is why no helmet standard in the world directly addresses a helmet's capacity to distribute impact forces. Perhaps why not, will be cleared up shortly.

4.2 Brain Injury Mechanisms

The brain, of course is not the only thing inside the skull. About 20% of that space is occupied with blood and cerebrospinal fluid. The brain itself, of which nearly everyone in the world has seen a picture, so we won't bother putting one here, is a rather gelatinous blob weighing about 1400gm in the adult human being. Over 75% of it is water (some of your friends may have more). The remainder is a soup of lipids, proteins, carbohydrates, and a few other organic and inorganic compounds spread more or less throughout. What enables the brain do its brain-like thing is the complex network of nerve fibers. There are around 100 billion (that's right *billion*) neurons imbedded within each of our brains. This neural network is rivaled in complexity only by the sophisticated three dimensional web of veins and arteries feeding and carrying blood to and from the brain. Brain injury will occur if the nerve fibers or the blood vessels are distorted too much. Typical injuries to the brain are:

Concussion. Having one's *bell rung* is perhaps something you are not unfamiliar with. Concussion is the least severe form of coma and as such does not necessarily imply loss of consciousness. The mechanics of concussion are not well understood as the symptoms, dizziness, brief loss of memory, nausea, perhaps slower reaction times, are outcomes that are of a generalized *self reported* nature. This neurological condition is due to a transient disruption of nerve tissue throughout the brain from which one expects to recover without significant long term consequences. There is no vascular injury with a concussion (i.e., no ruptured blood veins or arteries). If the head motion is very severe, this diffuse generalized injury pattern can lead to long term loss of consciousness, a coma from which one may possibly never awaken.

Contusion. A contusion is a bruise. A brain contusion is a localized area of the brain in which many small blood vessels have been ruptured. This can appear near the inner surface of the skull or deep within the cranial cavity. And though a loss of consciousness may occur (due to accompanying neurological damage), the contusion itself causes a disruption in the overall blood flow within the brain and the consequences can be dreadful.

Hemorrhage. A fancy word for bleeding usually associated with one or more vessels that have broken due to being stretched too much or from being severed. Again it is possible to suffer a brain hemorrhage without significant loss of consciousness but if not treated, the results can be fatal.

Hematoma. Another fancy word, this meaning the collection or pooling of blood at some location within the cranial cavity. A subdural hematoma is located between the brain and its outer covering, the dura. An epidural hematoma is located between the dura and the skull and is most often associated with the disruption of blood vessels within the bone where a skull fracture occurs. The biggest problem with a hematoma is that it creates increased pressure within the skull and causes the brain to deform to accommodate the collection of fluid.

Edema. This is not really an injury as such, but a consequence of any of those other injuries. Swelling of the brain due to compromised blood flow and associated nerve damage has drastic consequences as the increased pressure further restricts the flow of blood to and within the brain.

In the beginning, our understanding of the biomechanics of brain injury was, well, unclear. And to a great extent it remains that way. As Lombard (remember him from Chapter 1?) and coworkers put it in 1951,[16] *"There is a bit of confusion in the literature concerning the mechanisms of mechanical injury to the brain".*

Thirty years later, referring to head injury criteria employed in modern car crash testing, Goldsmith[17] observed that, *"The state of knowledge concerning trauma of the human head is so scant that the community cannot agree on new and improved criteria though it is generally admitted that present designations are not satisfactory".*

When you think about it, this situation is not entirely to be unexpected. How in the

world can you quantify the degree of violence of head impact to a living person?

Beginning in the early 1940s, in what were the first of several attempts to try to relate external loading to brain injury, researchers at Wayne State University in Detroit[18] impacted living dog's heads. Perhaps not surprisingly now, they observed that the harder the dogs were struck, the more likely or the more serious a head injury would be. In later experiments, they applied jets of air directly to animals' exposed brain. They noted a correlation between the force of the air and the duration of exposure to the blast and the severity of concussive effects.

A few years later, other investigators[19] continued this line of enquiry with a different model. They dropped cadavers onto their heads from different heights onto a flat steel plate until they could produce a skull fracture. Not because they were interested in seeing what it would take to *produce a skull fracture*, because they were more interested in finding out what it would take to produce a concussion. Wait a minute you're saying. How can you *knock out* a cadaver? Isn't he already beyond that stage? Read on.

What they did was to attach instruments called linear accelerometers to the cadaver heads in their tests. In those days, acceleration was typically measured in Gs, the unit of gravity. (10Gs for example means speed is changing ten times faster than that of an object in a perfect vacuum free fall. Another way of looking at it is, if you undergo an acceleration of 10Gs, every part of your body seems like it weighs ten times its normal weight).

In these experiments they also monitored the pressure inside the cadaver skull during impact as well as the head acceleration. By examining acceleration and relating it to those tests when a fracture occurred, they devised a crude relationship between the probability of concussion, the average head acceleration in Gs and the time duration of the impact. That this should relate to brain injury, particularly concussion, was imbedded in their idea that nearly everyone who sustains a skull fracture *sustains a concussion*. An adequate description of the head response, i.e., its movement, was felt to be contained entirely within the linear acceleration-time history during the impact. This *history* lasts only a few thousands of a second with maximum accelerations typically 100 to 300Gs.

By combining all their data, along with other estimates from accidental free falls, they developed what became and what is still referred to as the Wayne State Concussion Tolerance curve[20]. This function attempted to relate the level of tolerable linear acceleration and how long that acceleration lasted to whether or not a concussion could be expected.

One of the many problems with this approach is that most people who receive a concussion, or many of the other kinds of brain injury, do so without having their skulls fractured. Another problem that followed and that has lingered for years was the idea that brain injury was *caused* by linear acceleration.

By 1953, the helmet industry was coming to grips with some of these biomechanical concepts as evidenced in the following text from an American football helmet patent (US 2,634,415). Something of an oversimplification perhaps, but the inventors recognized that accelerating the head can injure the brain even if the skull does not fracture.

A head jolt properly may be defined as a sudden and/or severe change in the direction in which the head is moving, or the velocity with which it is moving, or both. The avoidance of sharp and/or severe head jolts is of vital importance. The human brain floats in the skull much as the yolk of an egg has floating suspension in its associated egg white. A sharp or severe jolt can rupture an egg yoke without fracturing the egg shell. Similarly, a sharp or severe jolt can cause fatal injury to a human brain without fracturing the skull which houses it, and often with only minor, if any evidence of injury at the outside of the head. There have been many such fatal injuries in the playing of football.

Readers with a technical background will recognize *jolt* as being a definition of acceleration.

Meanwhile, on the other side of the pond, a research physicist in the Department of Surgery at Oxford University, one A. H. S. Holbourne, hypothesized that the predominant cause of brain injury was not linear motion at all, but rather was due to rotation of the head[21]. Holbourne maintained that you could disturb/distort/disrupt the contents of the skull much more readily by rotating the head than by accelerating it linearly — the same way you could with say, a bowl of soup, if you spun the bowl rather than if you just pushed it across the table (keeping of course a lid on the bowl to more closely simulate a closed head so the *brains* don't spill out.).

In the meantime, most researchers in the US continued to be hung up on the idea that linear acceleration was the most important mechanism. By the 1970s, other US research-

ers, notably Ommaya and coworkers[22] who had subjected live monkeys to linear and angular impact motions, had concluded that *no convincing evidence has to this date been presented which relates brain injury and concussion to translational motion of the head...*

Nowadays, internal damage to the brain as a result of head impact is being studied with complex mathematical models that can actually predict the amount of deformation that occurs to the various parts of the brain tissue for different types of impact. Some investigators have even gone so far as to put mathematical helmets on the mathematical heads to see what the mathematically predicted effects are. To do so, in addition to modeling the skull, its contents, and the helmet's geometric and physical properties, one has to completely characterize the motion of the head in all three dimensions, including all linear and rotational components

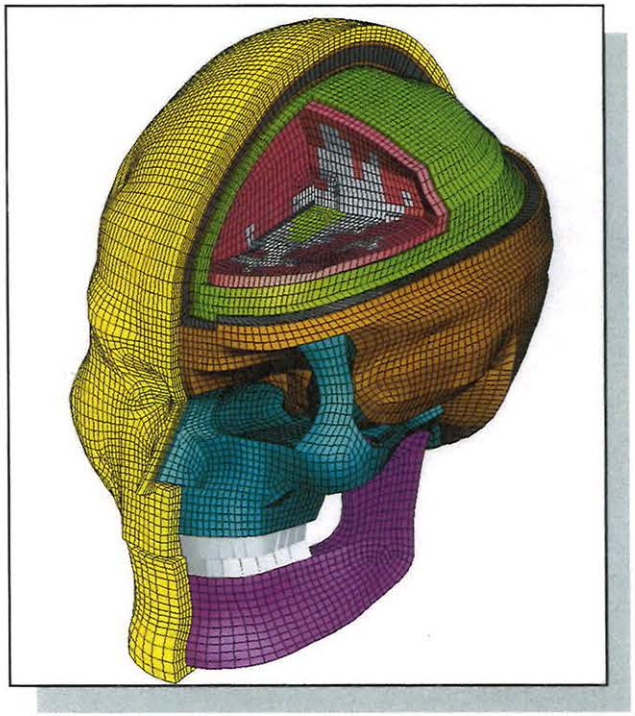
The Wayne State University Head Injury Model (WSUHIM) is a finite element model of the human head developed by Zhang et al [23]. According to Zhang,

The model has over 335,000 elements with an element size of 2-3 mm. The WSUHIM simulates all essential anatomical features including the scalp, layered skull with an outer table, diploë, and inner table, dura mater, falx cerebri, tentorium, arachnoid, pia mater, sagittal sinus, transverse sinus, cerebral spinal fluid (CSF), hemispheres of the cerebrum with distinct white and gray matter, cerebellum, brainstem, lateral ventricle, third ventricle, and bridging veins. The model has a detailed facial structure including the zygomatic bones, maxillae, hard palate, lacrimal bones, nasal bones, turbinate bones, vomer, and mandible.

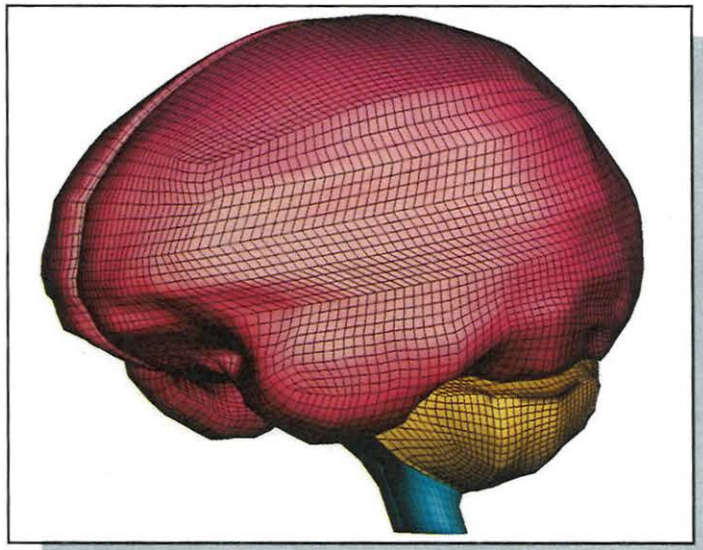
If you can grasp all that, you've probably already got a degree in medicine if not mathematics. *A total of 15 distinct material compositions are defined for the brain and surrounding tissues.*

As models like this continue to evolve, it will become possible to predict the exact nature and extent of head injury for any presumed impact to the head of a human being — and the effects of various safety devices such as helmets.

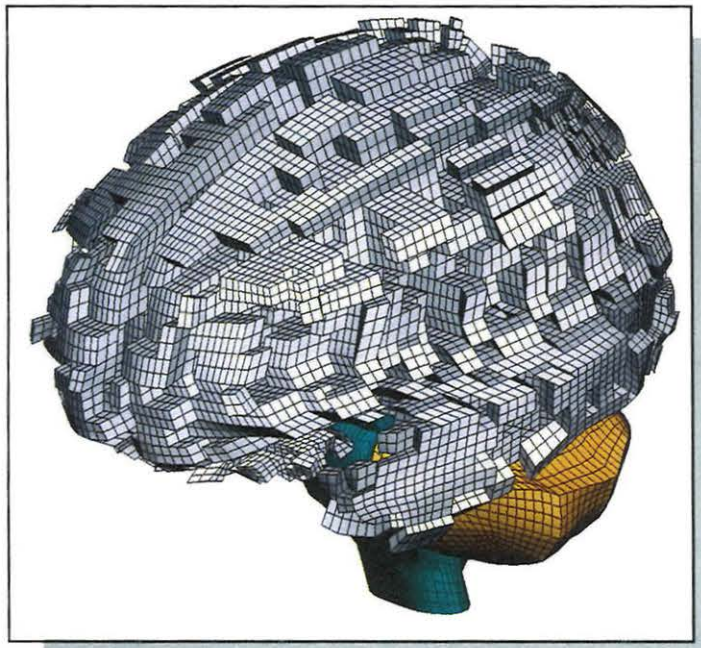
One of the most important studies of head injury to living human beings was undertaken by Biokinetics and Associates during the early 2000s. Under contract to the National Football League, game play video recordings of collisions between NFL football players that resulted in concussion (to one or the other combatants) were analyzed in minute detail to determine the precise characteristics of the head motion associated with mild traumatic brain injury[24]. Dozens of such cases were recreated using instrumented car crash test dummies. These data are now being employed, using precise mathematical models of the brain such as the WSUHIM, to determine the magnitude and the distribution of the internal brain deformation that was associated with each case.



This is an illustration of the Wayne State University finite element mathematical model of the human head. It is shown in section to illustrate the various components of the head. These include the scalp, the facial bones, the skull, and underlying membranes as well as the different aspects of the brain itself. *Courtesy Liying Zhang, Wayne State University.*

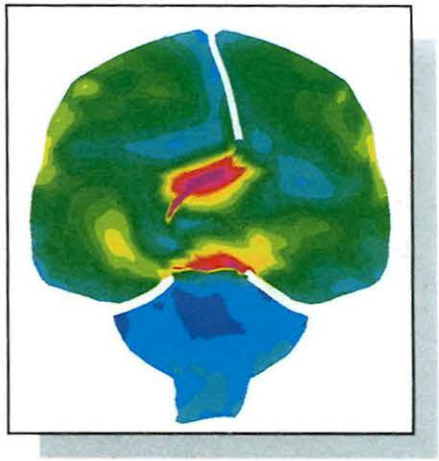


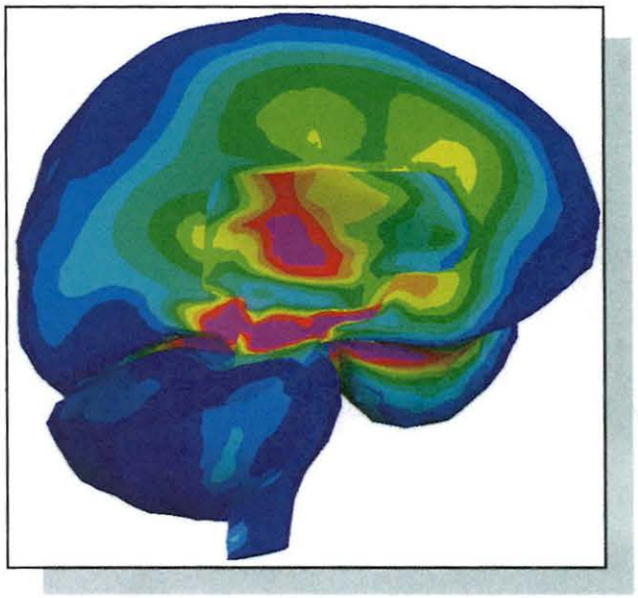
Made up of thousands of tiny mathematical building blocks, the entire mathematical WSUHIM brain is shown here. The outer part of the brain the grey matter appears pink here.



Beneath the grey matter one finds the white matter seen here. As in each subsystem of the mathematical head, each tiny block is not rigid but is assigned the properties of the appropriate brain matter so that it deforms in an appropriate manner.

These two figures show the distribution of strain or distortion at different sections of the brain at an instant during a simulated head impact. The model will predict how these strain patterns change in time. Shown here is when these strains are maximum at the mid brain region. The hotter red colors denote high strains while the cooler blue colors are lesser degrees of distortion. This particular simulation is that of one of a NFL football player who was concussed during a game.





Now here's where helmet standards and standard test methods come in. If a helmet doesn't work to protect the noggin from those nasty things discussed in this chapter, it really doesn't matter how well it may fulfill all the other design parameters.

5 Standards Development

Think about it. Suppose you're the President of Magnificent Helmets Incorporated and some guy shows up one day with a helmet he has just invented that he claims will protect the head better than your current model — in fact better than any helmet anywhere in the world. How can you possibly verify his claim? Well you could ask him to put it on, whack him in the head and see how he makes out compared to being whacked while wearing the current Magnificent helmet. Or you could take his word for it, go into production, sell a few thousand and wait for the lawsuits to start. Neither approach makes a lot of sense.

What you need is some kind of laboratory test that will enable you to determine the protection afforded by a specific design if worn by a real person. To do *that* means, in addition to knowing a little about the nature of the head injuries you're trying to prevent and that your tests somehow reproduce the threats that a user is apt to experience, you'll need some test surrogate, i.e., a *dummy,* to stand in for the real human. On top of that, your tests will have to provide a measure of some sort that allows you to determine whether in fact a design is better or worse than some other, i.e. that it passes or fails some criterion.

OK, as you've seen by now, there are three important features a helmet should possess that must be evaluated in helmet performance standards. In order of increasing importance, they are penetration resistance, retention capability and. impact attenuation. That is, the ability to stop a sharp object from making contact with your head, the ability of the helmet to remain properly in place on your head when you need it most, and most importantly, the ability to resist an impact to the head and to do so in a way that reduces the probability of skull fracture and brain injury.

If you really want to get a good overview of the complex helmet standards developmental history, you should check out Ed Becker's paper, which is pretty accurate to 1998.[25] We'll stay here with the *thumbnail sketch* approach, but even this will get confusing. There may just be too many organizations in the world writing helmet standards for too many different kinds of sports helmets.

As was mentioned before, performance standards for sporting helmets actually have their origins in the first of all such standards — that of the British Standards Institute BS 1869-1952 Crash Helmets for Racing Motorcyclists. This was followed two years later by BS 2826-1954, Protective Helmets and Peaks for Racing Car Drivers. Both standards provided tests to determine the energy dissipation capability of a helmet when subjected to a known impact.

Meanwhile in the US, Snively founded the Snell Memorial Foundation, the sole purpose of which was to develop and promulgate performance standards for auto racing helmets. Today, the Snell label continues to appear on many high performance helmets. Over the years it introduced new standards for many other forms of protective headgear in a variety of fields including skiing, bicycling, auto and kart racing, harness racing, as well as motorcycling and horseback riding. The SMF even has standards for moped riders and for non-motorized activities like skateboarding. Though some maintain that the Foundation's test methods and criteria are old fashioned, there is no question that in North America, Snell is continuing to *push the envelope* of helmet technology and the helmet industry has produced far better helmets than the world could have otherwise expected. Through the efforts of people like the Foundation's Executive Director, Ed Becker, George Snively's legacy continues.

By 1961, the American Standards Association ASA, an umbrella organization made up of users, manufacturers as well as independent technical types, had established a helmet standard committee. By 1966 it had published its first standard for *Vehicular Users*. Later, the ASA became the American National Standards Institute ANSI and its Z90 committee handled all things helmet related. Its standard for motorcycle helmets ANSI Z90.1-1971 was adopted by the Department of Transportation and became the national standard for motorcycle helmets in the United States FMVSS218. It has hardly changed since, though it was under review in 2006. ANSI's only other contribution to helmet standards was (following the lead of the BSI in 1970 and the Snell Memorial Foundation in 1973) the development of the

first national bicycle helmet standard Z90.4-1984. This voluntary standard was adopted by those manufactures that chose to do so. ANSI also tried to produce a football helmet standard but that was not successful.

Encouraged by the ongoing research at Wayne State University, athletic products manufacturers in the US decided to try to implement some of the research findings to improve football helmet performance. To this end, the National Operating Committee on Standards for Athletic Equipment was formed in 1969. NOCSAE designated one of the world's preeminent neurosurgical researchers, Voigt Hodgson of the Gurdjian-Lissner Biomechanics Laboratory at Wayne State University, as its chief investigator, and in 1974 its first standard for football helmets was published. Following Hodgson's retirement, David Halstead of the Southern Impact Research Center in Tennessee, and longstanding Chairman of the ASTM F08.53 helmet committee, was appointed as technical director of NOCSAE. Under his guidance NOCSAE has since developed and published performance standards for helmets for lacrosse, polo, baseball batters, even hockey. NOCSAE periodically reviews its standards, but they do not change very often.

In Canada, standards are developed and maintained by the Canadian Standards Association. Using The BSI as a model, CSA not only publishes standards but it also maintains a strict quality assessment program to which certified manufacturers must abide. When they do, they get a CSA sticker to place inside the helmet. CSA's first hockey helmet standard used a very old BSI hard hat standard as a guide. Published first in 1975, it was subsequently upgraded in 1983 and 1990. In 2006 it was under review again. It is the only sports helmet standard of any consequence administered by CSA. All others, cycling, motorcycling, skiing have been pre-empted by various US standards. In the US, hockey helmets are certified by Hockey Equipment Certification Council HECC to meet the ASTM 1054-99 standard for hockey helmets. In Europe, the prevailing standard is that of ISO10256-2003.

In the meantime, another US standards group, the American Society for Testing Materials ASTM, formed helmet subcommittees of its own. Their work effectively surpassed the work ANSI had done. Today ASTM has standards for hockey, equestrian sports, skiing, and snowboarding as well as for mountain biking and football. These too are self-certifying standards — that is you don't have to use them and if you say you do, then you do. That is, there is no certification agency overlooking these things. The only exception is in the case of bicycle helmets. In early 2000, the ASTM standard was essentially adopted *as is* by the US Consumer Product Safety Commission CPSC as its own. It now has the teeth of the law on its side.

In Europe, things were not entirely dormant. On the contrary, as far back as 1960, the International Standards Organization ISO formed a technical subcommittee to look into helmet issues. In 1970, ISO published its Recommendation R 1511. Though directed exclusively at motorcycling headgear, a major contribution was the issuance of a draft standard for headforms DIS 6220-1983. This DIS is referenced to this very day in nearly every helmet standard in the world. With the creation of the European Economic Community, the task of implementing helmet standards was one of insuring conformity. Standards developed largely by ISO became CE Norms or standards. Such CENs have now been published for most sporting endeavors.

5.1 Impact Testing

The ability to attenuate shock loading is the most crucial part of any sports helmet design. How to test for this feature has been the subject of considerable debate and confusion over the years. To be able to test for this feature in a laboratory setting is no easy matter and requires consideration of at least the following questions:

What is the nature of the test head upon which the helmet is to be *worn*?

What are the characteristics of what will do the hitting?

How hard will we hit it?

Where on the helmet shall we hit it?

How many times at each site will we hit it?

How many different impact sites are appropriate?

Under what environmental conditions shall we hit it?

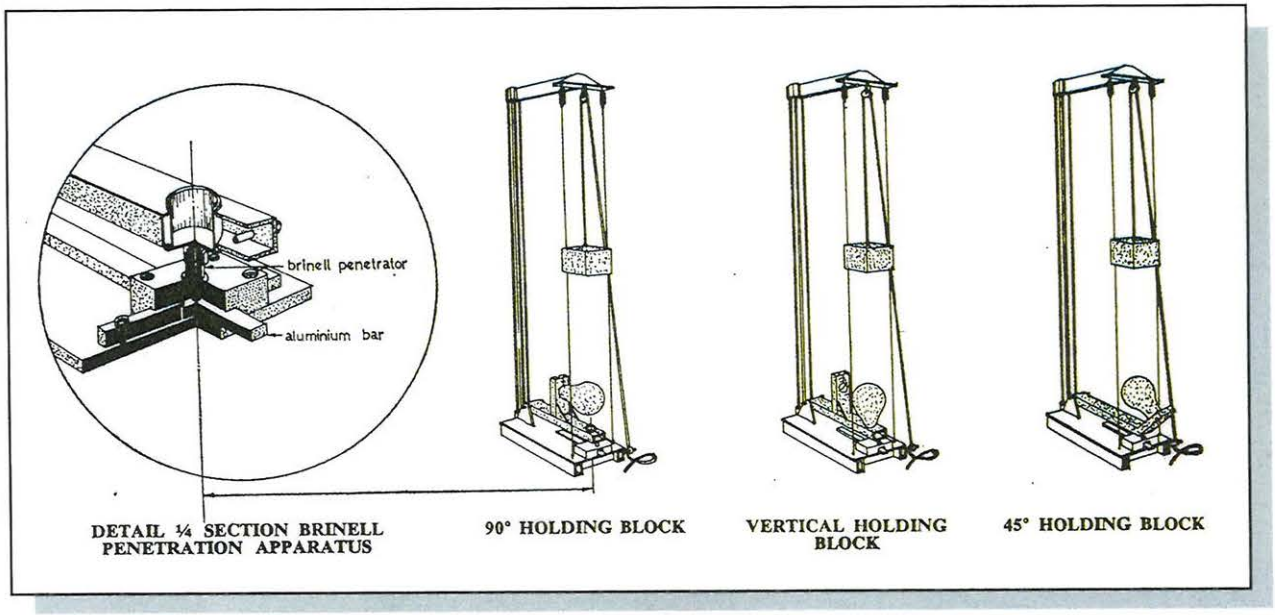
How do we take into account different sizes?

Are children's helmets treated differently?

What exactly are we going to measure?

5.1.1 Test Methods

Regardless of the particular method employed, there is the following general procedure: The helmet to be tested is fitted to a test headform of the appropriate size as if it were worn by a real person. The helmeted headform is then subjected to a blow from the outside and the *response* of the headform is measured. To date this has been done in one of two ways. In the earliest standards, the helmet was worn by a stationary headform that was struck by an impactor and the force transmitted through the helmeted headform was measured. Force transmitted could be measured electronically or mechanically. Mechanical measurement was still the approach until 1990 in the CSA hockey helmet standard. As seen in the figure here, a wooden block was dropped onto the stationary headform (at one of six possible sites). The force was measured by determining the size of an impression created in a standard piece of aluminum created by a conical metal dowel placed under the headform and resting on the aluminum plate. Since the hardness of the plate was known, the smaller the impression, the lower the force transmitted.



Early CSA method for impact testing of hockey helmets. These different set-ups allow the striker to impact any of six predetermined sites on the helmet. *With permission of the Canadian Standards Association.*

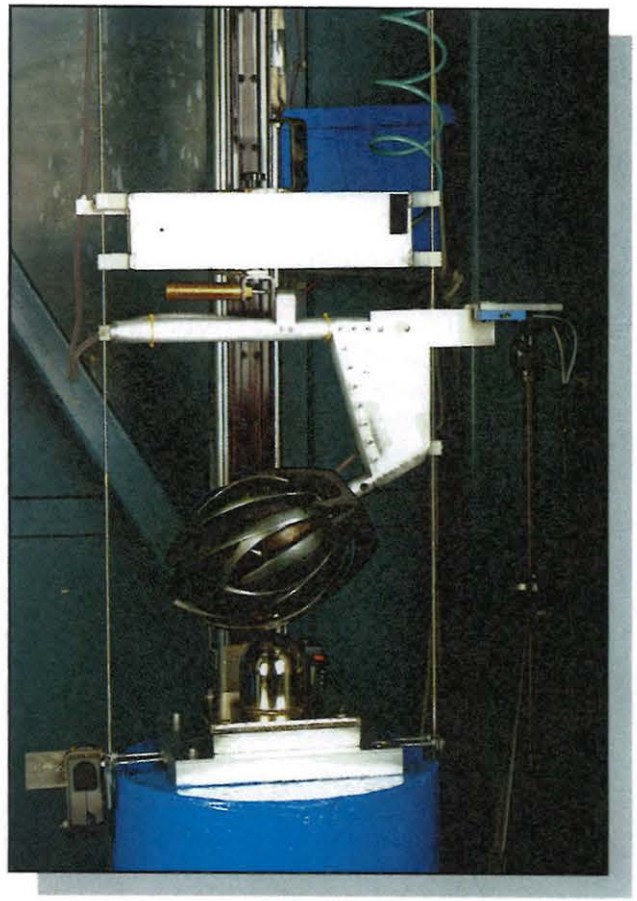
The other, now most common way, is to allow the helmeted headform to fall freely onto an anvil of some predetermined shape and to measure the acceleration (strictly speaking, the deceleration) of the helmeted headform. An electronic sensor, an accelerometer, is imbedded at the center of the headform to provide the information. (A third way, first devised by Snively in 1957, starts with a stationary headform and a free falling striker. Upon impact the headform accelerates. Fifty years later, a variation on this approach is again being considered in a revision to the NOCSAE standard test method[27]).

The most common approach used by current helmet standards is to employ what has been called *guided free fall*. Freely falling means that the impact is generated simply by allowing the helmeted headform to drop under the influence of gravity. In these cases the helmeted headform is attached to a *drop frame* that is guided, usually by steel wires or rods so that it lands in the right place. The headform can usually be positioned with respect to the frame, so that when the assembly is dropped, the helmet orientation and hence the helmet impact site is established.

The height from which one drops the helmeted headform varies from standard to standard and in some way reflects the expected violence of an impact that may occur when actually used by a wearer. Similarly, you might expect, the object onto which the helmet is dropped reflects what a user might encounter in the real world. Wrong! Standards testing cannot possibly contemplate the vast array of objects people might encounter with their heads. Instead a standard flat steel plate is the most common anvil. A *kerbstone* anvil is also often used, as is a hemispherical anvil. Not that either of these are realistic items one might actually strike but rather they represent severe impact surfaces that test the overall capacity of the helmet. One particularly severe anvil used in equestrian helmet standards is the one intended to represent a horse's shod hoof.







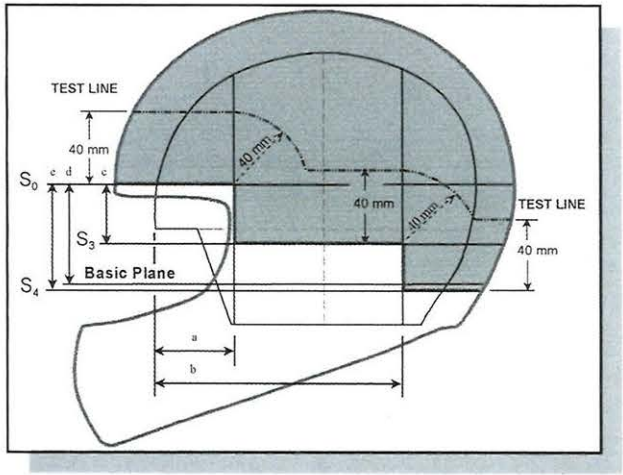
This is a typical drop tower, twin wire guided, free fall apparatus. The drop frame to which the helmeted headform is attached is released and the helmet strikes, in this case, the hemispherical anvil. *Photographed by Stephen Fenn courtesy of Biokinetics and Associates Ltd.*

Beyond the factors of what do you hit it on and how hard do you hit it are the matters of where precisely on the head do you expect impact protection to be provided and how many times do you impact it at the same site? The former issue is usually considered in standards under *extent of coverage* or *impact test zone* requirements. Nearly everyone would want to protect as much of the head as is feasible. Yet not every helmet user is going to tolerate a deep-sea-diver-like dome on his head. The test zone is different for different helmet standards again, most often reflecting what the user is willing to wear. However even the most stringent of standards, let's say the new FIA race car driver standard, requires impact protection over a surprisingly small part of the head.





These are typical of the steel anvils used in routine standard helmet testing. Some are definitely more aggressive than others. *Courtesy of Biokinetics and Associates Ltd.*



This illustrates the extent of coverage (the gray shaded area) and the test zone in the Snell SA 2005 and FIA 8860-2004 standards. The various S dimensions are for different headform sizes. The actual region wherein impact testing can be conducted is above the dashed TEST LINE. *With permission of the Snell Memorial Foundation.*

In order to establish that protection is provided *anywhere* within the test zone, *everywhere* in the zone has to be tested at one time or another. Other helmet standards take a different approach and simply identify a number of specific sites on the helmet that must be tested. The NOCSAE standards are of this nature, as is the CSA standard for hockey helmets. The argument that a manufacturer could actually have a defective helmet at sites that are *not* tested is probably not very sound. (They'd have to work very hard to deliberately try to fail if the helmet met the requirements at the prescribed sites.)

In terms of the number of impacts per site, athletic helmet standards recognize the repetitive nature of the sport for which they are intended and typically subject the helmet to three successive impacts at each site. Crash helmets on the other hand usually require just one substantial impact per site. However Snell and other motorcycle and auto racing standards impact more than once at each site.

Why, you might ask, would any crash helmet standard *require* that the helmet have to deal with two hits at the same identical site? Well, it may be that accident victims strike their heads twice at the same site during a crash. Or maybe, having sustained one major impact and being protected, the wearer goes out, has *another* crash and hits the same spot again. The truth is that the innovators of these standards did not have much accident data and went on gut instinct and what seemed at the time to be *common sense.*

When the first British racing helmet standards were published in 1952 and 1954, a 10 pound wooden block was dropped *once* from a clear height of 9 feet onto the front or back of the helmet. In the first North American standard for racing crash helmets, published in 1959[28], there appeared the statement: "The helmet must withstand a minimum of *two* blows at this energy level without failing the above conditions." The conditions involved dropping a 16 pound hemispherical weight *twice* onto the front, back, and sides of the test helmet from a clear height of 6 feet. It has been argued that the helmet standard pioneers really wanted to hit the helmet just once at each site, but at an energy level higher than the lab would allow. So they did it twice at a lower level instead. The current Executive Director of the Snell Memorial Foundation, Ed Becker has himself noted, "Some experts reason that a two impact protocol is appropriate because many crashed helmets show evidence of multiple hits. However, I have become convinced that the real reason is the limited ceiling height in most helmet test laboratories. Rather than cut a hole in the roof, the standards developers decided to hit the helmet twice."

It has also been suggested that someone back in the late 1950s observed that this *Styrofoam*® stuff that was showing up in helmets was not good at sustaining a second blow because it crushed so well and *What if someone hit his head a second time at the same place? Maybe the standard should require that the helmet be hit twice — just in case.* These practical considerations have resulted in this requirement continuing to appear in North American standards to this day, when, in fact, what evidence there is suggests wearers of crash helmets hardly ever hit their heads more than once *at the same place in the same crash.* The problem is that by requiring a motorcycle or auto crash helmet to tolerate the rare two (*sometimes three*) blows at each site, you compromise its ability to protect against the far more common single impact. In fact, there is a growing body of opinion that this approach has led to auto and motorcycle helmets in North America that are not as good as they could be.

Nowadays, in Europe, motorcycle helmet standard ECE Reg. 22 stipulates only *one* impact per site. This appears to be in accord with the most recent accident investigation data[30]. The new FIA standard for auto racing headgear also stipulates just *one* impact per site with a variety of anvil shapes. Europe moves on. North America is lagging behind.

The other factors to consider are related to the environment in which the helmet must function. To cover most eventualities, the tests described above are done on helmets that have been baked in an oven first or soaked in water, stuck in a freezer for many hours, as well as normal ambient conditions. Some standards expect the helmet shell to be doused in hydrocarbon fluid before being impacted. And if that wasn't enough, all standards require that these tests be done on all sizes of helmets that are being produced and sold. Well then, the headforms that are to be used had better be available in a range of sizes and of the proper shape — and perhaps they should also be *humanlike* in some way?

5.1.2 Headforms

Biomechanically speaking, not much was known or utilized in the early standards. In fact the word biomechanical had hardly been invented. The importance of proper anatomical shape of the head was appreciated and a table documenting the polar coordinates of a test headform, for a medium sized head, was provided. These same dimensional characteristics are employed to this day though they have been extrapolated to a variety of sizes. Their origin however remains something of a mystery. In the old days, given the shape of the *pudding bowl* helmet, there was no need to have such dimensional precision below the hat band region so only the top of the head was modeled.



The test headform of the British Standards Institute c. 1952. *Photo courtesy of Biokinetics and Associates Ltd.*

From the point of view of test headform biofidelity nothing was implemented. In fact the original test headforms were constructed of wood — wood with rather precise characteristics vis *...a wooden headform shall be made up of horizontal laminations of birch having a density of 40-45 pounds per cubic foot at a moisture content of 12 percent. The wood shall be straight in grain, free from defects and free from dote.* Clearly this was no attempt to model the mechanical characteristics of most human heads. Rather it reflects the British engineers' fascination with properly stipulating a reproducible piece of test equipment. (Dote apparently is another way of saying *rot*.)

The test headform that Snively employed in the first Snell standard was not wood but rather was described as being of K-1A magnesium alloy. Dimensional characteristics were not specified. Other than weighing 12 pounds, there were no other biofidelity requirements and there was no consideration regarding different sizes of heads and helmets.

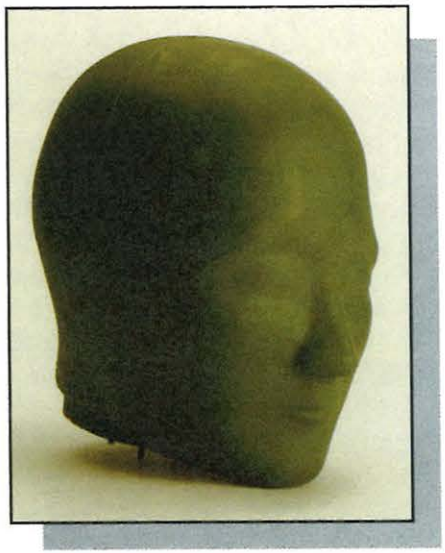


George Snively setting up the original *swing away* impact test, c. 1960. *Photo courtesy of the Snell Memorial Foundation.*

When the ASA introduced its standard in 1966, the swing away method was an option for manufacturers. However the drop frame approach became the norm and the headform specified was a rather un-anthropomorphic K-1A alloy item. This headform was subsequently adopted by ANSI and the US Department of Transportation. Since testing was always above the hat band, no attempt was made to model the lower region of the head.



This example of the ASA/ANSI/DoT test headform has obviously seen better days having survived a lot of helmet failures. *Photo courtesy of Biokinetics and Associates Ltd.*



This is NOT the head of the Jolly Green Giant. It's an original NOCSAE headform used to test football helmets. They were produced in different colors so that different sizes were immediately obvious. *Photographed by Stephen Fenn courtesy of Biokinetics and Associates Ltd.*

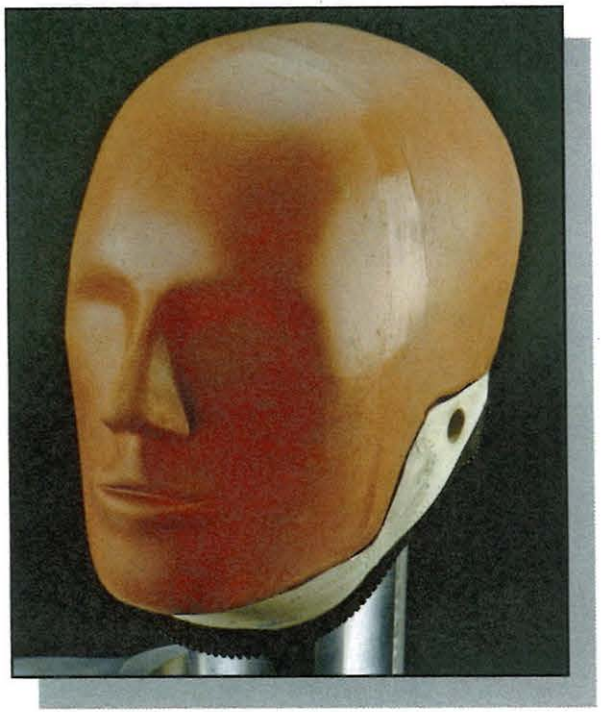


A newer NOCSAE headform said to be more durable, more anthropometrically correct and with molded in reference lines to assist with helmet positioning. *Photographed by Stephen Fenn courtesy of Biokinetics and Associates Ltd.*

Hodgson at Wayne State University recognized the possible importance of headform biofidelity and with others[31] developed a test headform to better simulate the dynamic response of the human head. Based upon cadaver data the headform modeled both the geometric, inertial and frequency response characteristics of the head quite well. Being a complete head/face structure certainly made getting the correct weight distribution a lot easier. Originally in one size only, several sizes were subsequently developed. Like the human skull, and unlike any headforms before it or since, the NOCSAE headform would fracture if impacts were too severe — not a particularly good feature of a piece of test equipment.

While the US experimented with different interpretations of the *proper* head, Canada and Europe adopted the ISO DIS 6220 headform geometry. Canadian standards employed a twin guide wire drop frame system whereby a partial headform was suitable.

The European CEN standards use a different system and a full headform is required — something like the NOCSAE heads. The EN960 headforms look a lot like this:



This is a Hybrid3 automotive crash test dummy head that has been modified by Biokinetics to facilitate helmet testing. It is being considered as an alternative to the NOCSAE head in football helmet testing. *Photographed by Stephen Fenn courtesy of Biokinetics and Associates Ltd.*

In regard to motorcycle helmets, huge strides were made in Europe with the publication of the new ECE Reg 22 -05 motorcycle helmet standard. It now represents the state-of-the-art in performance specifications in this area, partly because of biomechanical considerations and partly because of solid accident data analysis. Importantly, it and all modern CEN protocols allow the headform to freely fall without any of the usual customary (guided free fall) constraints of other contemporary standards. This, it is argued, allows the head to respond in a more human-like fashion better permitting the implementation of human based criteria. Unlike many other standards (NOCSAE excepted), each of the five ECE test headforms comprise the entire head rather than the partial headform employed by others. The anthropometrics are considered good and various sizes of appropriate mass and mass distribution are used.

Snell and ASTM have since adopted the ISO headform shape (much like the CSA headform seen here) but they are made of magnesium alloy. However, rather than adopting different masses for the different head sizes like the CE norms, Snell and ASTM employ headforms all of the *same* mass (5kg.). [LATE BREAKING NEWS – ASTM voted in 2006 to switch to variable mass headforms for its hockey helmet standard and Snell is proposing something similar for its children's motorsports helmet standard.]



This is an ISO headform used in the CSA motorcycle and bicycle helmet standards. Rather than being of metal, it was cast in a tough epoxy resin. *Photographed by Stephen Fenn courtesy of Biokinetics and Associates Ltd.*



This is the smallest of the ISO headforms, ISO-A, and is the shape of the corresponding EN 960 headform used in European helmet standards. *Photographed by Stephen Fenn courtesy of Biokinetics and Associates Ltd.*

5.1.3 Failure Criteria

In spite of recent revelations about the mechanisms of brain injury, to this day, no helmet standard directly tests the capacity for a helmet to protect against brain injury due to movement other than simple linear (straight line) motion. Additionally, they generally do not directly address load distribution and they do not address rotational motion. The reasons these standards actually work in spite of these apparent shortcomings are likely because:

Load distribution becomes a problem relative to skull fracture only when forces become high. Forces are high when linear acceleration is high so limiting it, limits the other.

High levels of rotational motion are induced by impact. The overall severity of that impact is judged by the resulting linear acceleration of the head. It has been demonstrated that high linear acceleration comports to high rotational acceleration. So again, limiting one, to a great extent takes care of the other.

There are four different failure criterion functions used in helmet standards testing. All are based on linear acceleration. They are

Maximum headform acceleration. The most common of helmet failure criteria, it is simply the highest value of the acceleration that a test headform achieves during impact testing.

Maximum acceleration plus *dwell times*. This approach also sets limits on how long, i.e. how many milliseconds, the acceleration can persist at various levels less than the maximum.

The Gadd Severity Index SI[32]. This is a function of the shape of the acceleration waveform that considers not just the maximum value but also the average acceleration during the impact.

The Head Injury Criterion HIC. A complex mathematical function that searches for the most dangerous part of the acceleration waveform, and sets limits on how bad it can be.

Various standards employ various combinations of the above as shown in the table below. You'd think there would be agreement among all standards since, whether you're in a bicycle race in France, skiing in Colorado or car racing at Laguna Seca, it's the same human head being protected. The fact is different standards groups think *their* approach is better than the other guy's. How each of these functions is used will become apparent (hopefully) as we get into this.