CP 18-1

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December 15, 2017

BY ELECTRONIC MAIL

Alberta Mills
Acting Secretary
U.S. Consumer Product Safety Commission
4330 East West Highway
Bethesda, MD 20814

Re: Hövding Sweden AB Requesting an Exemption from the Testing Requirements of the Bicycle Helmet Standard for Certain Head Protection Devices

Dear Secretary Mills:

Enclosed herewith for filing with the Commission is a Hövding Sweden AB Petition Requesting an Exemption from the testing requirements of the Bicycle Helmet Standard for certain head protection devices. Hövding is also requesting a hearing before the Commission to address the issues raised in its Petition.

I have also mailed the original and five copies, along with a copy of this letter, to you pursuant to the applicable Rules. If there is more I need to do to be sure that this Petition gets to the Commissioners, please let me know.

Sincerely,

Elliot Belilos

EB:mts
Enclosure

CP 18-1

BEFORE THE
U.S. CONSUMER PRODUCT SAFETY COMMISSION

REQUESTING AN EXEMPTION FROM THE TESTING REQUIREMENTS OF THE BICYCLE HELMET STANDARD FOR CERTAIN HEAD PROTECTION DEVICES

PETITION OF HÖVDING SWEDEN AB

BEFORE THE
U.S. CONSUMER PRODUCT SAFETY COMMISSION

REQUESTING AN EXEMPTION FROM THE TESTING REQUIREMENTS OF THE BICYCLE HELMET STANDARD FOR CERTAIN HEAD PROTECTION DEVICES

PETITION OF HÖVDING SWEDEN AB

INTRODUCTION

Pursuant to Sections 7 and 9 of the Consumer Product Safety Act, 15 U.S.C. §§ 2056 and 2058, U.S. Consumer Product Safety Commission ("CPSC") regulations, 16 C.F.R. §1051 and the Administrative Procedure Act, 5 U.S.C. §553(e), Hövding Sweden AB ("Hövding") files this petition requesting an exemption from the testing requirements of the CPSC's Bicycle Helmet Standard, 16 C.F.R. §1203. In support of the petition, and as required by regulation, Hövding submits the following information.

INTEREST OF THE PETITIONER

Hövding Sweden AB manufactures inflatable protective headgear for bicyclists. The company is located at Bergsgatan 33, 214 22 Malmo, Sweden.

The company was started by two Swedish students of industrial design, Anna Haupt and Terese Alstin, who decided to research the feasibility of developing a bicycle helmet that people would be happy to wear – whether they had to or not. Their master's thesis resulted in the concept of an airbag bicycle helmet.

The airbag helmet quickly gained attention for its innovative design. In 2006 the product's designers won the Venture Cup competition, where young entrepreneurs develop their idea into a sustainable business plan. Hövding Sweden AB was founded the same year. It took seven years to transform Hövding from a concept into an approved and certified product.

From those beginnings, Hövding has grown from just two people with a great idea to a NASDAQ-listed company. To date, more than 60,000 Hövding devices have been sold. Hövding's airbag for cyclists is available in 16 markets across Europe and in Japan. The headquarters are located in an old chocolate factory in Malmö – the sixth greatest cycling city in the world.

As discussed below, the CPSC standard for bicycle helmets does not anticipate helmet designs other than the traditional hard shell-type helmet and, consequently, the Hövding helmet cannot meet the U.S. standard, in particular, the testing requirements of the standard. This is in spite of the fact that there are ample testing and experiential evidence that the Hövding product provides significantly superior head protection to that provided by helmets that do comply with the U.S. standard. Unless an exemption is granted for the Hövding airbag for cyclists, it cannot be sold in the United States and U.S. consumers will be denied the superior protection afforded by the product.

THE PRODUCT

The Hövding airbag for cyclists is designed to protect a rider bicycling in an urban environment or on the road and is not designed for mountain or stunt biking (for which specialized helmets are available). It is designed for cyclists of ages 15 and over. Hövding is worn around the neck like a collar. The small gas inflator that activates the airbag is in a holder in the collar on the cyclist's back. The inflator uses helium to inflate the airbag.

To use, the Hövding is powered by a battery that is easily charged through a USB charger (a cable is included with the product). A fully-charged battery lasts for approximately 9 hours of active cycling. LEDs at the front of the collar show the battery level, and a low battery level is indicated by both light and sound.

The product is made of an ultra-strong nylon fabric that, when inflated, will not rip when scraped against the ground. The inflated Hövding protects nearly all of the head, while leaving the field of vision open. The inflated airbag covers a much larger area than a traditional cycle helmet and is designed according to current accident statistics to provide protection where it is needed most.

The airbag fixates the neck and provides extremely soft and gentle shock absorption. The pressure remains constant for several seconds, making it able to withstand multiple head impacts during the same accident. After that, the airbag slowly starts to deflate.

Thousands of tests have been done, re-enacting cycling accidents using stunt riders and crash-test dummies, to collect the specific movement patterns of cyclists in accidents. In parallel, normal cycling data has been collected using test cyclists wearing Hövding in everyday cycling. Based on this collected data, the company has developed an algorithm that can distinguish normal cycling from accidents.

When activated, Hövding records the cyclist's movements 200 times a second. In the event of an accident, the cyclist's abnormal movement is detected and the airbag inflates.

As noted above, approximately 60,000 Hövding devices have been sold in Europe and Japan. The company is aware of approximately 1600 deployments *with none of these incidents resulting in serious, lasting head injury*. The company is aware of only one incident where the device did not deploy as expected and in this instance, the cyclist did not suffer lasting injury.

RISK OF INJURY ADDRESSED BY PETITION

While no state (nor the federal government) mandates helmet use by adult bicyclists, many local jurisdictions have such laws. Those laws, for the most part, reference the CPSC bicycle helmet regulation, requiring that helmets meet the CPSC standard. Consequently, it is neither economically or legally possible to market a bicycle helmet that does not meet 16 C.F.R. §1203.

The purpose of the regulation is to reduce injuries or deaths to bicyclists from head impacts. While the standard has been in place since 1999, serious cycling injuries and deaths continue to be a significant problem. According to a recent report, "[n]ot only did bicyclists as a percentage of crash deaths remain stubbornly unchanged at 2.3 percent, but they represented the largest increase in fatalities (12.2%) when compared to all roadway user groups. During [2015] 818 bicyclists died on U.S. roadways. . . ."[1]

Helmet use does reduce injuries or deaths for cyclists involved in accidents. However, while "54 percent of the [adult] cyclists killed in 2015 were not wearing a helmet . . . 17 percent were helmeted and the status of 29 percent was unknown."[2] The majority of deaths occurred on roadways in urban areas[3], the type of cycling environment for which the Hövding was designed. This data shows that serious head injuries and deaths occur in the U.S. even when a cyclist is wearing a helmet. If, ***in the best case***, almost 20 percent of fatalities occur even when a helmet is worn, then a head protection device, like the Hövding, that can reduce these fatalities will both further the purposes of the regulation and save lives.

Testing has shown that the Hövding airbag provides a greater level of safety than do the traditional hard shell helmets. In a study by Stanford University, *attached as Appendix A*, researchers compared the head protection of the Hövding to that of helmets that passed the CPSC standard.[4] Among other things, they found that the Hövding reduced concussion risks to below 10% compared to 68% with a standard helmet—an 8-fold improvement. The Hövding reduced severe head injury risks to below 20% and fatality risks to below 2%. The study concluded that "[t]his airbag helmet design almost completely eliminates the risks of severe head injury and fatality . . . ."

It is important to note that the Stanford study does recommend that "before this technology becomes widely available, airbag helmets need more reliable impact triggering technologies and should be evaluated in more realistic bicycle accident simulations."[5] The company's aggressive efforts to investigate the circumstances around deployments and the real-world positive safety results of the Hövding compared to traditional shell helmets address those concerns. The Hövding is a dynamic product, with each deployment providing an opportunity for Hövding to refine its algorithm with ever-increasing real-life accident scenarios. Indeed, the SP Method 43, the test method under which the Hövding is tested for use in Europe, specifically tests for proper deployment in typical accident scenarios.

The findings with respect to the Hövding's ability to reduce the risk of concussions and severe head injuries is also supported by a 2015 study done by the Swedish insurance company, Folksam. *See Appendix B for study*. The Folksam study compared the Hövding with five shell-type helmets (some of which are sold in the United States and meet the U.S. standard) and found that the Hövding "showed the overall best result." The study described the relative safety attributes in the following manner:

> The Folksam test shows a relatively large variation in the test comparing the helmets' capacity to absorb impact energy (48-242 g). Experience from American football indicates

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[1] "A Right to the Road: Understanding & Addressing Bicyclist Safety," Report of the Governors Highway Safety Association, 2017 ("GHSA Report"), p 8, http://www.ghsa.org/sites/default/files/2017-09/2017BicyclistSafetyReport-FINAL.pdf.

[2] GHSA Report, p 20.

[3] See, *Insurance Institute for Highway Safety Report on bicycle fatality trends*, http://www.iihs.org/iihs/topics/t/pedestrians-and-bicyclists/fatalityfacts/bicycles .

[4] Kurt, Mehmet, et al., *Modeling and Opitimization of Airbag Helmets for Preventing Head Injuries* (Stanford University), Annals of Biomedical Engineering (2016), Appendix A.

[5] *Id.*, at 7.

> that head injuries start to occur at 60-100 g (Zhang et al 2004). In addition, the risk of skull fractures could be dramatically reduced (from a 40% to a 5% risk) if the translational acceleration would be reduced from 250 g to 180 g (Mertz et al. 1997). Helmets should therefore be designed to reduce the translational acceleration well below the legal requirement (250 g), provided that they also take into account the rotational forces to avoid brain injuries. The translational acceleration is mainly associated with the risk of skull fracture whereas the rotational acceleration and rotational velocity are associated with brain injuries. The results from the Folksam helmet test clearly show that it is possible to design a helmet that meets the legal requirements with a wide margin. The conventional helmet POC Octal reduced the energy that the head form was exposed to with almost half of the threshold of the requirements (135 g compared with 250 g). *However, the Hövding 2.0., a head protector that is inflated during an accident situation and acts as an airbag for the head, obtained the best results. The translational acceleration was 48 g, a value almost 3 times better than the best conventional helmet, POC Octal.* [Emphasis added]

Folksam Study at 15. While the CPSC Standard requires the impact energy absorption level to be below 300 g, the European Standard (SP-Method-4439) provides a more stringent requirement – i.e., 250 g. The Hövding provides impact energy absorption protection at a level (48 g) that virtually eliminates the risk of serious head injury.

While additional research is always useful, both the Stanford and Folksam studies are consistent in finding that Hövding provides a higher level of head protection than do traditional helmets that comply with the CPSC standard and, consequently, will reduce injuries and deaths.

EXISTING STANDARDS

The CPSC bicycle helmet standard, 16 C.F.R. §1203, applies to "any headgear . . . intended to provide protection from head injuries while riding a bicycle." The regulation describes testing methods that must be used to determine compliance with performance criteria set out in the test methods—that is, the test methods describe not only how to test but the minimum results needed to pass the test. The regulation, on its face, contemplates the testing of shell-type helmets. Alternative designs, while they are deemed to be helmets, cannot use the test methods set out in the regulation and so, by extension, cannot comply with the standard.

The European Union has a similar standard for shell-type helmets, EN 1078. In addition, it has a standard for personal protective equipment (which includes bicycle helmets of any type) that must be met before the European "CE" mark can be applied to designate compliance. Because non-shell type helmets are outside the scope of EN 1078, the SP Technical Research Institute of Sweden developed an alternative standard for inflatable head protective devices so that these products could comply with the personal protective equipment directive and receive the "CE" mark. *See Attachment C, SP-method 4439.*

The Swedish standard covers the range of issues regulated by the CPSC standard including such things as construction, sizing and ergonomics, minimum protected area, shock absorbing capabilities, wear resistance and labeling. As discussed above, in some instances the level of protection in the Swedish standard is higher than that in the CPSC standard. For example, the CPSC standard specifies that the peak acceleration of any impact shall not exceed 300 g's while *SP-method 4439* specifies that the peak acceleration does not exceed 250 g's.

The standard also treats two issues that are often raised as concerns about this product—that the airbag will not inflate when needed or will inflate unnecessarily. The standard includes requirements to test the triggering system including resistance to false accident detection during normal bicycling. Requirements for warnings and labeling information are also set out in the standard. In summary, the Swedish standard provides a comprehensive range of protective requirements, compliance with which equals or exceeds the protection provided by the CPSC standard.

REQUESTED ACTION

Hövding respectfully requests that the Commission exempt inflatable head protective devices for bicyclists from the requirements of 16 C.F.R. §1203, the bicycle helmet standard, if those devices meet the requirements of SP-method 4439 and are so certified. Hövding further requests that CPSC do so through an interim final rule in order to expedite the introduction of this life-saving product to the U.S. market.

The Commission's test protocol for bicycle helmets, when promulgated, did not envision the innovative airbag technology developed by Hövding. The test methodology is specifically designed to test the peripheral vision, positional stability, dynamic strength of retention system, and impact attenuation of traditional shell helmets. These tests cannot be applied to the Hövding, even though the Hövding offers the rider superior head protection in the event of an accident.

The peripheral vision test (1203.14), the positional stability test (1203.15), the retention system test (1203.16) and the impact attenuation test (1203.17) cannot be applied to the Hövding because the airbag is not inflated until it is deployed in an accident. Indeed, by its very nature, the Hövding ensures no obstruction to the cyclist's peripheral vision during use. The positional stability and the retention system tests are not necessary because the non-deployed Hövding is worn around the neck, not on the head. Similarly, the impact attenuation test cannot be performed on an un-deployed Hövding. The testing is designed for a conventional shell helmet. SP-Method-4439 was specifically designed to ensure that the Hövding satisfies at least the same performance criteria as conventional shell helmets, *i.e.,* protects the cyclist's head in the event of an accident. In fact, SP-Method-4439 ensures greater impact protection than does 16 C.F.R. §1203, requiring acceleration force no greater than 250 g (compared to a limit of 300 g in the CPSC Standard).

The Commission has authority to take the requested action under the Administrative Procedures Act (APA) and its own regulations. It has issued exemptions from regulations in the past.[6] Indeed, it is well established that Federal Agencies have inherent authority under the APA to grant exemptions from their own regulations. "An agency's authority to proceed in a complex area [of] regulation by means of rules of general application entails a concomitant authority to provide exemption procedures in order to allow for special circumstances." *United States v. Allegheny-Ludlum Steel Corp.,* 406 U.S. 742, 755 (1972). In fact, Agencies not only *may* but *must* consider granting exemptions from general rules in special circumstances.[7]

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[6] The lead determinations are exemptions from testing requirements. See also the exemption for dyed textiles from the lead content testing requirements.

[7] *See WAIT Radio v. FCC,* 418 F.2d 1153, 1157 (D.C. Cir. 1969) ("The agency's discretion to proceed in difficult areas through general rules is intimately linked to the existence of a safety valve procedure for consideration of an application for exemption based on special circumstances. [Some cases warrant] serious consideration of meritorious applications for waiver, and a system where regulations are maintained inflexibly without any procedure for waiver poses legal difficulties.").

The CPSC has the authority to issue the requested exemption without APA Notice and Comment, as the requested action would be considered to be an adjudication rather than a rulemaking under the APA. Where an agency's decision to issue an exemption "rest[s] on considerations peculiar to each individual case," the agency's "action in deciding whether to waive its [requirements] is more in the nature of an adjudication than of rule-making."[8]

The requested action will ensure that the helmets contemplated by the regulations continue to be tested for compliance. However, it will allow new, innovative products to enter the U.S. market if they can demonstrate that they meet safety standards that provide the equivalent or higher levels of safety than that provided by the U.S. standard.

Testing and experience shows that the Hövding airbag for cyclists will reduce serious injuries and fatalities. Without action by the CPSC, American consumers will not have access to this dynamic product and unnecessary injuries and deaths will continue.

CONCLUSION

Hövding has developed an innovative head protection device that has the potential to save lives and reduce the number of serious head injuries for cyclists. The current CPSC bicycle helmet standard does not contemplate a product like Hövding. We ask the CPSC to exempt the Hövding from certain testing requirements of the CPSC Bicycle Helmet Standard, provided that it meets SP-method 4439. Hövding further requests that CPSC grant the requested exemption through an interim final rule in order to expedite the introduction of the Hövding to the U.S. market.

Respectfully submitted,

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[8] *Nuclear Data, Inc. v. Atomic Energy Comm'n,* 344 F. Supp. 719, 723 (N.D. Ill. 1972); *see also Keller Commc'ns, Inc. v. FCC,* 130 F.3d 1073, 1076–77 (D.C. Cir. 1997); Int'l *Union v. Fed. Mine Safety & Health Admin.*, 920 F.2d 960, 964 (D.C. Cir. 1990) (stating that agency's exercise of power to "exempt mines from . . . interim [safety] standards" was an example of "case-by-case adjudication"); *Basic Media, Ltd. v. FCC,* 559 F.2d 830, 833 (D.C. Cir. 1977) (finding that where there are "particular cases of hardship," agencies may make individual dispensations or grant exceptions through case-by-case adjudication); *Turro v. FCC,* 859 F.2d 1498, 1499–1500 (D.C. Cir. 1988) (noting only two uses of exemptions).

Modeling and optimization of airbag helmets for preventing head injuries

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Abstract

Bicycling is the leading cause of sports-related traumatic brain injury (TBI). Most of the current bike helmets are made of extended polystyrene (EPS) foam and ultimately designed to prevent blunt trauma (*e.g.*, skull fracture). However, these helmets have limited effectiveness in preventing brain injuries. With the availability of high-rate MEMS sensors and high energy density batteries, a new class of helmets, *i.e.*. expandable helmets, can sense an impending collision and expand to protect the head. By allowing softer liner medium and larger helmet sizes, this novel approach in helmet design provides the opportunity to achieve much lower acceleration levels during collision and reduces the risk of brain injury significantly. In this study, we first develop theoretical frameworks to investigate impact dynamics of current EPS helmets and airbag helmets - as a form of expandable helmet design. We validate our theoretical models with post mortem human subject (PMHS) and anthropomorphic test dummy (ATD) drop test experiments. Peak accelerations obtained from these experiments with airbag helmets achieve up to an 8-fold reduction in the risk of concussion compared to standard EPS helmets. Furthermore, we construct an optimization framework for airbag helmets to minimize concussion and severe head injury risks at different impact velocities, while avoiding excessive deformation and bottoming-out. An optimized airbag helmet with 0.12 m thickness at 70 kPa reduces concussion risk to under 10% at 6.6 m/s head impact velocity compared to 68% with a standard EPS helmet. This airbag helmet design almost completely eliminates the risks of severe head injury and fatality for impact velocities up to 9 m/s.

INTRODUCTION

Traumatic brain injury (TBI) is a major cause of death and disability in the United States, contributing to about 30% of all injury deaths[15]. Although contact sports elicit most of the media attention, bicycling is the leading cause of sports-related TBI. According to the American Association of Neurological Surgeons, bicycling was responsible for about 86,000 of the 447,000 sports-related brain injuries treated in emergency rooms in 2009[20]. Bicycling was also the leading cause of sports-related brain injuries in children under 14, causing 40,272 injuries in total[45]. Furthermore, many bicycle crashes are unreported and therefore not included in official statistics. In fact, some studies estimate that only less than 10% of bicycle crashes are officially reported[9,24].

The classical approach in designing a bicycle helmet has not been sufficiently effective[8]. Most currently used bike helmets are made of extended polystyrene (EPS) foam with a thin plastic shell. Studies have shown that although wearing the EPS helmet decreases the risk of severe head injury by approximately 75% , the reduction in mild traumatic brain injury (mTBI) rates is statistically insignificant[2,43]. The main variables involved in designing a bicycle helmet are the size and stiffness of the helmet, which directly influence the helmet's energy absorption efficiency. Numerous studies show that low helmet compliance especially in children is mostly related with self-image and comfort problems[17,23]. Due to these aesthetic as well as practical concerns, helmet size has been limited to a few centimeters. These limitations have in turn governed the choice of material that can be used as liner. EPS has become the obvious choice given its light weight and impact absorption capacities.

The "Helmet Designer's Dilemma"[37] in Figure 1 describes a compromise between maximum force exerted on the head and the helmet liner's deformation limit. A spectrum of different type of materials can be used for helmet liners. A softer material can result in lower force levels, however it is more likely to reach the helmet deformation limit where bottoming out occurs. In contrast, a stiffer material results in lower deformation levels but higher forces. This is the fundamental trade-off in helmet design: stiff materials (e.g. current bicycle helmets with EPS foam) are required to prevent bottoming-out in severe accidents but are sub-optimal in lower accelerations (Figure 1). The current solution to this dilemma is depicted as the green curve, where the material exhibits a "force-limiting" behavior, therefore keeping the experienced force at an almost constant level at excessive deformations. Although current EPS foams are designed to have force-limiting, they fail to show these characteristics for impact loading[41].

The effect of size and stiffness in military helmet liners has been extensively studied. Moss *et al.* showed significantly increased protection with modest increases in military pad thickness[32]. The current pad is about three-quarters of an inch thick, and a pad-thickness increase of an extra quarter of an inch could make a large difference in reduction of head trauma. Adding even an eighth of an inch results in a 24% reduction in force on the skull. However, this size study was specific to the application of military helmet pads. These findings have also been confirmed for bicycle helmets, where thicker pads where shown to perform better under impact conditions[31,34]. In addition, softer helmets have been shown to reduce the amount of impact acceleration transfered to the head. Softer foams have been used to lower acceleration levels as a replacement to denser and stiffer foams[33]. Also for the same thickness and impact area, helmets with air-filled chambers faired better than foam pads[26,34].

Going back to Figure 1, we observe that unlike the amount of force that the head experiences during an impact, the size of a helmet is not a physical limit but rather a technological limit which can be eliminated by using an expandable airbag material by making use of the extra rattlespace (*i.e.*, maximum allowable space for the relative motion between the head and helmet in the direction of the

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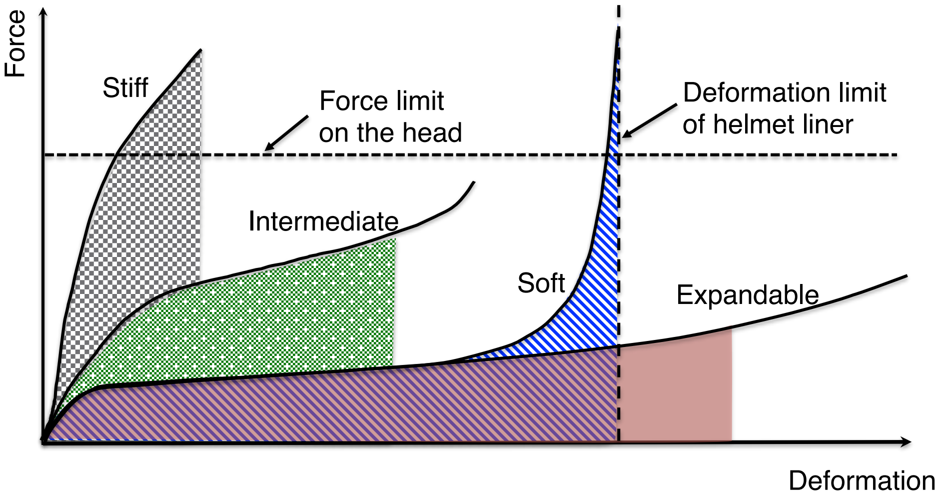


Figure 1. Material selection for helmet design: Spectrum of force-displacement for various helmet padding stiffness adopted from[37]. Stiff, intermediate and soft materials depict the ultimate trade-off a helmet designer faces for liner selection. To absorb a given impact energy (shaded areas under the force-displacement curves), a stiff helmet is likely to experience large forces whereas a soft helmet reaches to the deformation limit and bottoms out. Previously, intermediate approaches have been implemented by using polymeric foams. Another approach would be to extend the deformation capability of a soft helmet to achieve much lower force levels.

impact[5]). Also, the deformation limit shown in Figure 1 is usually lower than the actual size of the helmet. This, however, would not be the case with a collapsible gas-filled helmet: A gas-filled helmet would be able to use its full stroke length, which provides more time to absorb the impact energy before the material condenses and exceeds the force limit. Even though expandable helmets can significantly decrease the practical limitations regarding the helmet deformation limit, for years, the effect of increasing the size of the helmet and using a softer material has not been carefully studied because of the practical and technological obstacles. With the advent of inexpensive, high-rate MEMS sensors and high energy-density batteries, a reasonably sized ”expandable helmet” can sense an impending collision and expand to eliminate brain injuries in many scenarios. Air would be the ideal medium to utilize for such an expandable helmet design since it is fast-deployable and its mechanical paramaters can be tuned by merely adjusting the pressure value.

Recently, an airbag bicycle helmet called Hövding was invented in Sweden. It is in the form of a sash that inflates just before a head impact. One of the main concerns regarding Hövding and airbag helmets in general is the risk of bottoming out at low pressures and/or at severe impacts. Therefore, it is extremely important to scientifically evaluate this novel approach and airbag helmets in general. In a series of impact tests conducted by the Swedish company Folksam, Hövding helmet (with unreported pressure values) performed almost three times better than all the other conventional helmets in terms of peak accelerations at oblique impact tests (48 g vs around 175 g at 5.42 m/s impact speed)[18]. They also noted an average 60% decrease in rotational accelerations compared with conventional helmets.

In this study, we aim to determine the optimal pressure and size of an airbag helmet against linear accelerations. Therefore, we present a simple reduced order model for impact dynamics of airbag and EPS helmets. EPS helmets serve as a control group to test the efficacy of airbag helmets. We then experimentally evaluate the performances of EPS and airbag helmets by using drop tests. We conclude by proposing a theoretical framework for the optimization of a soft and expandable helmet. We compare the optimal behavior with that of an ideal polymeric foam and previously published theoretical performance limit for a free-falling object[5].

MATERIALS AND METHODS

The overall approach we followed in our study is as follows: In order to compare the effectiveness of EPS foam helmets and airbag helmets, we first modeled the impact dynamics of both helmets by assuming simplified geometries in the form of hemispherical shells (Figure 2). In order to validate our simple theoretical models, we carried out PMHS and ATD drop test experiments. Then, we compared the theoretical predictions for acceleration traces with drop test results. Finally, we proposed a theoretical framework for the design of a soft expandable helmet model. The design algorithm makes use of the developed impact dynamics model for airbag and EPS helmets to minimize peak acceleration at a given helmet size.

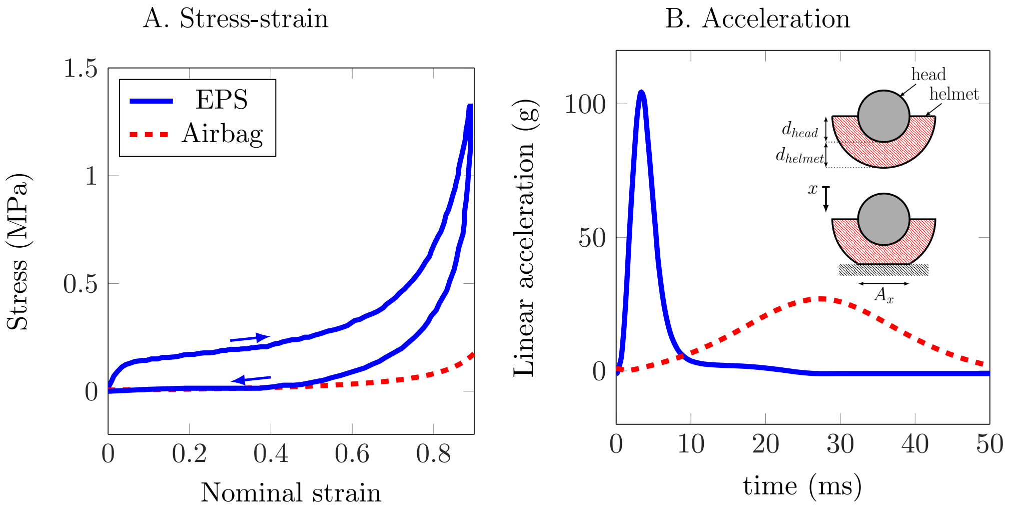
Analytical model of airbag and EPS helmets

In order to model the impact dynamics of an airbag, we started with a simple hemisphere geometry and derived the airbag deformation model (Figure 2B). This geometry and deformation model was first proposed in Esgar *et al.*[14] and was also considered in Do *et al.*[12] for impact attenuation of NASA's Orion Crew Exploration Vehicle. We then constrained the deformation of the hemisphere helmet up to the skull-helmet interface, *i.e.*, the helmet was effectively modeled with a shell geometry where the inner semi-circle represents the skull. Hemispheric impact geometry resulted in a contact area model which completely flattened at the deformation limit. We made use of the ideal gas law and derived the relationships for instantaneous pressure and contact area as a function of deformation of the airbag in the impact direction (Figure 2A, also see Supplemental).

Impact dynamics of the EPS helmet were modeled by assuming the same hemispherical shell geometry. For EPS material properties, we made use of the loading and unloading force-displacement curves of uniaxial compression of EPS20 foam (Figure 2A)[41]. Based on relations for bouncing of an elastic body on a rigid surface, we calculated the coefficient of restitution for the EPS helmet to be 0.30 (see Supplemental).

ATD drop tests

We instrumented a 50^{th} percentile headform (X2 Biosystems, Seattle,WA) with internal reference 3-1-1-1 accelerometer and gyroscope


A. Stress-strain

B. Acceleration

Figure 2. Impact dynamics of a hemispherical EPS and airbag helmet: To model the impact dynamics of airbag and EPS helmets, we constructed simple reduced order models by assuming hemispherical geometries. (A) Force-displacement curve for a hemisphere airbag with 35 kPa initial pressure and stress-strain curve of EPS20 element adapted from[41], (B) Acceleration profiles of hemispherical airbag and EPS helmets from a 0.6 m drop height. The geometry of the helmets is also represented.

array, which were considered as ground truths. The headform was dropped on an aluminum plate with a drop scaffold consisting of a net-rope mechanism. Before the drops, the heads were positioned in the net for the correct impact orientation, the rope was pulled to elevate the headform and then released (Figure 2). We used Bell Solar (Bell, CA) and Hövding (Hövding, Sweden) as representatives of EPS and airbag helmets respectively. We tested these helmets over varying drop heights between 0.6 and 1.8 m and pressure levels at 35 and 50 kPa (for the airbag helmet). We considered parietal and vertex orientations for the tests since these are the two most common head impact locations in bicycle accidents[11]. Each drop scenario was repeated 3 times and EPS helmets were replaced after each trial to prevent repeatability errors due to material failure (*i.e.*, fracture). Pressure of the airbag helmet was also measured before/after the tests to make sure there was no leaking, which would affect the performance. Contact forces between the helmet and the ground were measured for the dummy head free-fall experiments by using BodiTrack (Boditrak, Canada) smart fabric sensor (Figure 2).

PMHS drop tests

We instrumented a female cadaver head (aged ∼80yr) with a mouthguard utilizing 3-axis accelerometer and gyroscope[4]. We again tested Bell Solar and Hövding as representatives of EPS and airbag helmets respectively. Similar to ATD experiments, we tested these helmets over varying drop heights between 0.6 and 1.8 m and pressure levels 35, 50 and 65 kPa (for the airbag helmet). The same impact orientations as in ATD drop tests were considered. We carried out the PMHS drop tests by measuring the drop height and positioning the head manually to carry out a free fall onto an aluminum plate. We repeated each drop scenario 2 times. As in ATD drop tests, EPS helmets were changed after each trial to prevent errors due to material failure.

Injury Risk Evaluation

In evaluating the head injury risks for experimental and theoretical results, we first calculated the corresponding head injury criterion (HIC), which is the most widely used injury criterion[16]. We specifically utilized HIC$_{15}$, which is a measure of impact over 15 milliseconds. Previous studies have shown that a HIC$_{15}$ of 1000 corresponds to 50% risk of skull fracture[22], a HIC$_{15}$ of 700 is estimated to represent a 5% risk of a severe injury[29], and a HIC$_{15}$ of 250 to represent a 50% risk of concussion in athletes[42].

To assess the severity of the injury risks, we then made use of Abbreviated Injury Scale (AIS), which is an anatomical scoring system based on HIC$_{15}$[1,36]. We used two AIS score levels: AIS 2+ corresponds to moderate brain injuries, which is defined as classical concussion[40] and AIS 4+ represents severe head injuries (e.g., skull fracture)[40] and AIS 6+ represents fatality risk. We also evaluated the peak linear accelerations obtained from ATD and PMHS drop tests, which were defined as the peak value of the translational acceleration magnitude over time. Previously published data show that concussions have been observed for peak linear accelerations between 50 and 150 g[21,46].

Optimum expandable helmet design

In order to construct a theoretical framework and optimize the airbag helmet design for a given impact scenario, we first studied the effect of size for an airbag helmet for a head impact at 6 m/s. We then made use of the simple airbag model at the optimized size to minimize peak acceleration at impact velocities between 2-9 m/s by varying the pressure of the airbag between 20-100 kPa. We carried out numerical simulations over these system parameters and calculated the corresponding Abbreviated Injury Scale (AIS 2+) to assess the severity of the moderate brain injury risks. During the simulations, we cross-checked the size of the helmet against the maximum deformation during the impact to detect bottoming-out, which occurs when the deformation exceeds the size of the helmet. We considered pressure values corresponding to bottoming-out cases as "failure" and omitted them from the optimization procedure.

RESULTS

PMHS and ATD experiments

The results of PMHS and ATD experiments were summarized in Figure 3 in terms of the peak acceleration values and associated injury risks. The airbag helmet at 35, 50 and 65 kPa pressure values performed similary at 0.6 and 1.2 m drops, yielding around 20-40 g peak linear accelerations respectively (Figure 3A). For reference, we also superimposed results from a similar PMHS experiment from

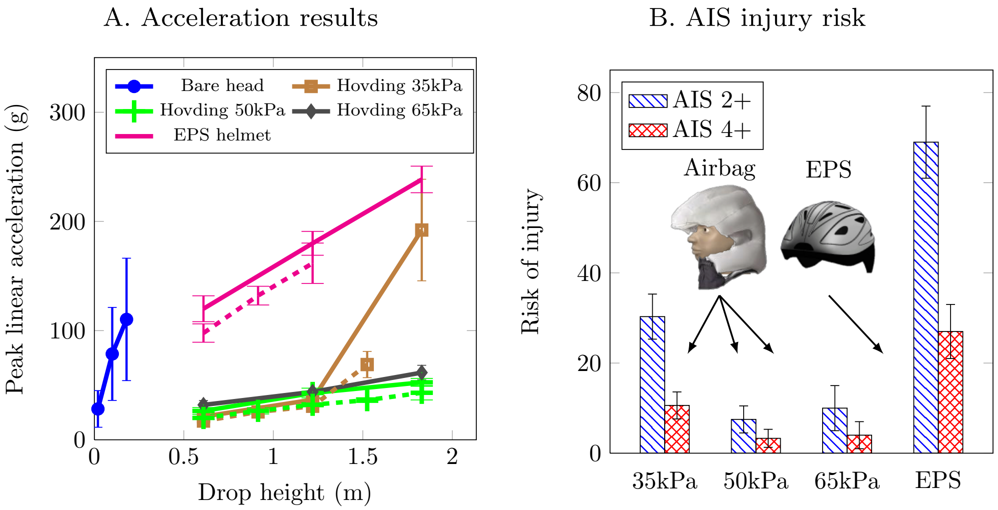


Figure 3. PMHS and ATD drop tests results: We carried out PMHS and ATD drop tests to validate our theoretical airbag and EPS helmet models. (A) Peak accelerations for airbag helmet (Hövding) and EPS foam helmet from PMHS (solid line) and ATD experiments (dashed lines) respectively. (B) Average mild and severe head injury probabilities (Abbreviated Injury Scale (AIS) 2+ and 4+ respectively) at 6 drop height for EPS and Hovding.

our group for bare head drops. Values reported for EPS helmet are consistent with those reported previously in the literature[6], where peak acceleration and HIC values at a 1.8 m drop were found to be 181 g and 1250 g respectively (Figure 3A). At 1.8 m drop, the airbag helmet with 35 kPa bottomed out, approximately resulting in acceleration values around 170 g. Interestingly, the airbag helmet at 50 and 65 kPa resulted in at least a 5-fold reduction in peak acceleration values compared with Bell Solar at every drop height, the maximum reduction (6-fold reduction) being achieved at 0.6 m. Directional dependence was not significant in the results with the exception of the bottoming-out case for Hövding at 35 kPa due to the varying thickness of the Hövding helmet at different locations.

We also compared the peak accelerations obtained from ATD drop tests with the results form PMHS experiments.(Figure 3A). Compared with PMHS drop tests, peak acceleration values obtained from the ATD drop test experiments were similar, resulting in similar peak acceleration values within 10% errorband. We observed that Hövding at 35 and 50 kPa yielded at least a 5-fold reduction in peak linear acceleration values compared with Bell Solar. In order not to damage the setup, we stopped testing the airbag helmet at 35 kPa for higher than 1.5 m, which was the onset of bottoming-out.

In our analysis, we considered AIS 2+ to represent mild-to-moderate brain injuries, such as concussion and AIS 4+ to represent severe head injuries, such as skull fracture. Similar to the reduction observed in peak linear accelerations, The AIS 2+ and AIS 4+ injury scores are reduced by 5-8 fold with airbag helmet (65 kPa) compared to EPS foam helmet (Figure 3B).

Analytical modeling of Airbag and EPS helmets

The main motivation beyond constructing analytical models was to develop a framework for expandable helmet design optimization. Figure 2B depicts the acceleration profile of the theoretical EPS helmet model from a 0.6 m drop height. We note that the impact duration predicted for an EPS helmet at 0.6 m drop is 4 times shorter (around 10 ms) when compared with that of the airbag helmet, which was around 40 ms (Figure 2B).

In order to move forward, we validated our theoretical models' predictions with PMHS and ATD experiments. The theoretical model for the airbag is able to predict peak linear acceleration values within a 5-30% error band (Figure 4C). In this model, the errors were larger for lower pressure values, which is to be expected since the deformation is more nonlinear in these cases. The theoretical model for EPS helmet was also able to predict linear acceleration trends quite accurately, with NRMS errors between 10-20% ATD and PMHS drop tests (Figure 4C).

Optimum Expandable Helmet Design

Size Optimization

There is a crucial trade-off between helmet size and performance in helmet design. It is apparent in Figure 1 that increasing the size of a helmet for a soft helmet has a pay-off in its performance, albeit with diminishing marginal returns after a certain size value. In Figure 5, we optimized Ogden material models to minimize peak linear acceleration values for varying helmet thicknesses at 6 m/s impact velocity in Figure 5A. The Ogden material model represents a hypothetical polymeric foam material, whose Ogden parameters are limited, to the author's best knowledge, within the extreme values reported in the literature[10] (see Supplemental). The Ogden material model was then optimized for varying helmet thickness values at 6 m/s impact velocity in Figure 5A to minimize peak acceleration such that the stress-strain curves can be thought as ideal hypothetical polymeric foams for helmet design at a given size (Figure 5A). As expected, the optimum foams become softer and their elastic deformation regions tend to dominate the material response. In Figure 5A, we also observed an abrupt change in the material properties for helmets larger than 5 cm, which is the critical helmet size value that allows for globally soft characteristics for the given 6 m/s impact velocity.

In Figure 5B, we took a closer look at the effect of the helmet size in helmet performance, which was partially depicted for polymeric foams in Figure 5A. The three curves in this graph represent the optimum HIC values of (1) optimum polymeric foam helmets from Figure 5A, (2) airbag helmets with optimum pressure values (by using the simplified airbag impact model) and (3) theoretically minimal HIC values[5] for varying size values between 2.5 and 18 cm, in the case of a 6 m/s head impact. The pressure of the optimum airbag helmet decreases as the size increases since the equivalent elastic stiffness needs to be smaller. Ideal airbag and foam curves have similar trends since both of the material models were made softer as the size increased (Figure 5A,B). In Figure 5B, we also superimposed the corresponding HIC values of 1.8 m ATD drop tests for Bell Solar and Hövding, which have corresponding average HIC values of 1080 and 220 respectively.

For the initial pressure optimization, we fixed our size to be 12 cm since after this size value, increasing the size has marginal

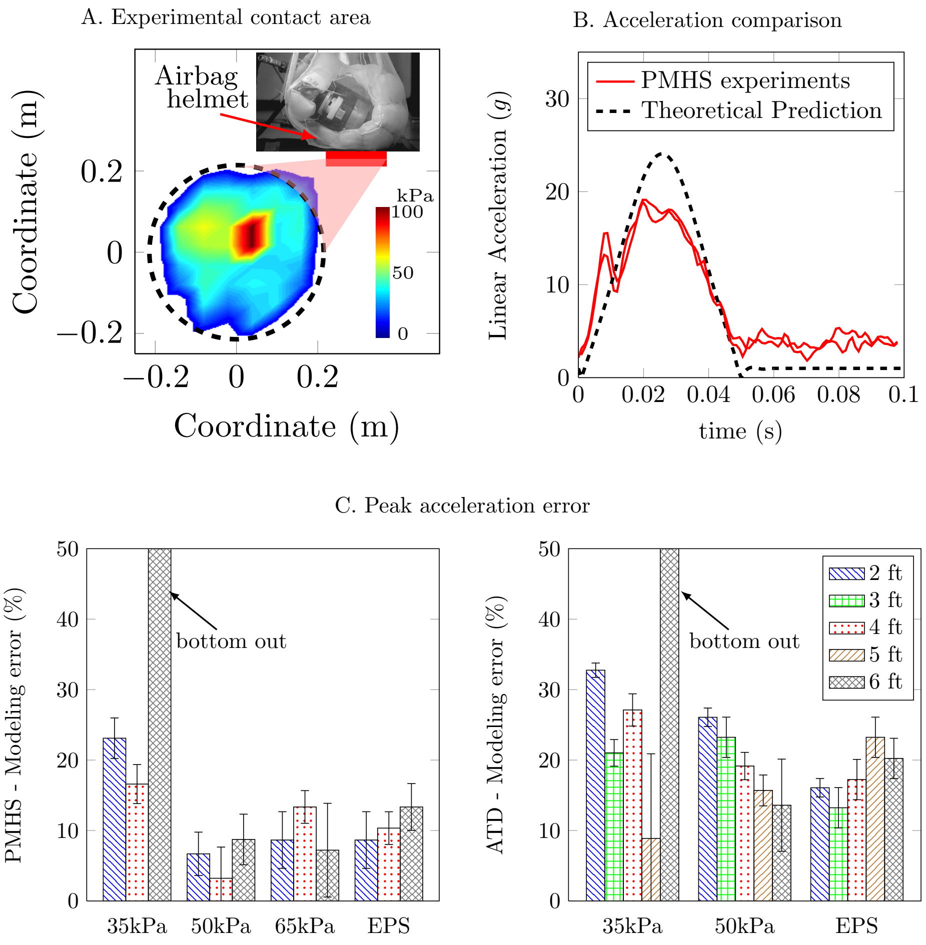


Figure 4. Validation of the theoretical EPS and airbag impact dynamics models: (A) Comparison between the empirical and theoretical (- - -) contact areas. The bumps on the surface of the Hovding restricts the contact area, therefore the theoretical airbag model shown in Figure 2B overpredicts the contact area. The contact areas for the analysis carried out in the papers are empirically extracted from the Boditrack data, an example of which is shown above. (B) Comparison between the experimental and theoretical linear acceleration response curves for 35 kPa Hovding at 1.8 m drop height. (C) Error graphs showing percent peak acceleration errors between theoretical EPS and airbag models shown in Figure 1 and 1) PMHS experiments 2) ATD experiments.

improvements (Figure 5B). We also wanted the size of the helmet not go over the average width of a male human shoulder in order to prevent causing the head to contact the ground before the shoulder[28].

Initial Pressure Optimization

Since we experimentally demonstrated that one can achieve a significant reduction in head injury risk with an airbag helmet for both severe and moderate cases, in this section, we investigated whether we can optimize the airbag helmet parameters even further to achieve greater injury risk reductions. We utilized the simplified airbag impact dynamics proposed (Figure 2) to simulate accident scenarios with varying head impact velocities between 2 and 9 m/s, which is a common head impact normal velocity range for bicycle accidents[3]. Our proposed optimum expandable helmet strategy is based on minimizing HIC at a given impact velocity for a fixed helmet size of 12 cm. We then calculate the corresponding AIS 2+ injury scores.

The results of this optimization are reported in Figure 6. As observed, up to 6.6 m/s impact velocities (federal standard)[44], an airbag helmet with 70 kPa pressure yields in sub-concussive threshold HIC values (AIS 2+ $<$ 10%). It was shown that, lower pressure values resulted in smaller HIC values while at the same time becoming more vulnerable to bottoming-out as the impact velocity increases. The bottoming-out region is represented by the hatched region in Figure 6. For extreme accident cases, where the normal velocity of the impact to the head was approximately 9 m/s, the airbag helmets with fixed size of 12 cm and pressures between 20-60 kPa bottomed out. However, an airbag helmet at 70 kPa reduces the skull fracture risk at these head impact velocities to around 20% (AIS 4+) and fatality risk (AIS 6+) below 1% (Figure 6). By using the EPS helmet theoretical model, we simulated an impact at 6 m/s and found the concussion risk to be at 68 % (Figure 5B).

DISCUSSION

The most common cycling accident scenario is a single fall, in which cyclists fall on their own[13,27]. The average head impact velocity in a single fall varies between 4.8 m/s and 6.2 m/s[3], which is close to the federal standard test speed of 6.6 m/s. In the context of these scenarios, our results highlight the limitations of the current 2.5 cm sized EPS foam helmets. We show that at a head impact velocity of 6.0 m/s, the current EPS foam helmet results in both a high risk of concussion (>68%) and a high risk of severe injury (>30%) (Figure 3B and Figure 5B). Even ideal foams and airbags below a size of 8 cm still result in significant risk of concussion (50%), thus necessitating larger helmet designs (Figure 5B). Expandable airbag helmets represent a practical method for increasing helmet size during an impact and our experimental results for Hövding (12 cm, 50 kPa) demonstrate that such designs can significantly curtail risk of concussions and severe injuries, reducing HIC scores five-fold compared to standard EPS helmets (Figure 5B). However, as the

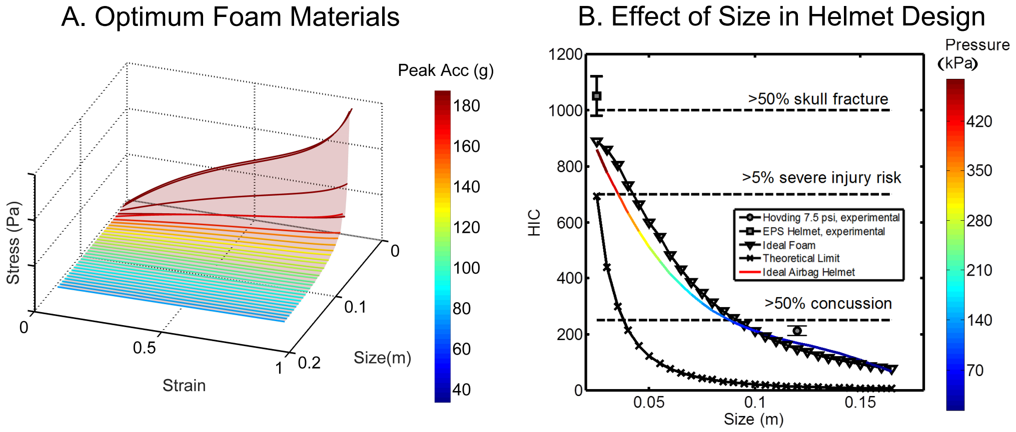


Figure 5. Limitations in helmet design with respect to size and material: (A) Optimum Ogden models that minimize peak accelerations for an impact velocity of 6 m/s. Foams are usually modeled by Ogden models so these can be thought as ideal hypothetical foams for helmet design. (B) Change of HIC values (at 6 m/s) depicted in (1) with respect to size. Theoretical limiting curve imply constant acceleration profiles. Constant HIC 250, 700 and 1000 lines are also plotted to show how the ideal foam performs with respect to varying size. It is shown that even with an ideal foam, if the helmet size is below 8 cm, there is a risk for concussion (HIC >250). Hövding (size, 12 cm) seems to be performing really close to an "ideal foam". However, EPS foam helmet appears even above HIC 1000 curve, which corresponds to a 50% probability of skull fracture.

head impact velocity increases, these airbag helmets have a higher risk of bottoming-out. Therefore, a careful optimization of initial pressure for a given accident scenario is required.

Our study of helmet size also provides a possible future direction for the study of expandable helmets. Since the properties of an expandable helmet (pressure and size) can be altered in real time, the optimized airbag helmet design can be pushed even further towards the theoretically minimal acceleration curve (Figure 5B). For instance, an active energy dissipation mechanism, such as a pressure relief system can be employed with an airbag impact protection system to minimize peak accelerations and/or head injury criteria (HIC) during the impact by using real-time sensory information.

Our study was solely designed to demonstrate a "proof-of-concept" for soft and expandable helmets. One main limitation here was the assumption of simple hemispheric geometry for airbag helmet impact dynamics. Due to the simple geometry, our model did not have directional dependence for impact dynamics. However, since our experimental results showed little variance for different impact orientations (parietal and vertex), we were able to verify our model. Another limitation of the study was that we confined our performance criteria of helmets solely to linear accelerations. We that rotational kinematics could play a significant role in head injury mechanism during bicycle accidents[25] and there have been efforts to design preventive equipment to reduce the effect of rotational kinematics.[19,30]. Therefore, an optimum expandable helmet should ideally help reduce rotational accelerations as well. In unpublished data from bicycle accident reconstruction simulations using the optimized airbag helmet from Figure 6, we have observed a similar reduction in other head kinematic parameters (*e.g.*, rotational acceleration) as well as different head injury criteria (*e.g.*, head impact power (HIP)[38]). Future efforts will therefore concentrate on the optimization of these helmets in different bicycle accident scenarios. We also plan to study the effect of expandable helmet impact

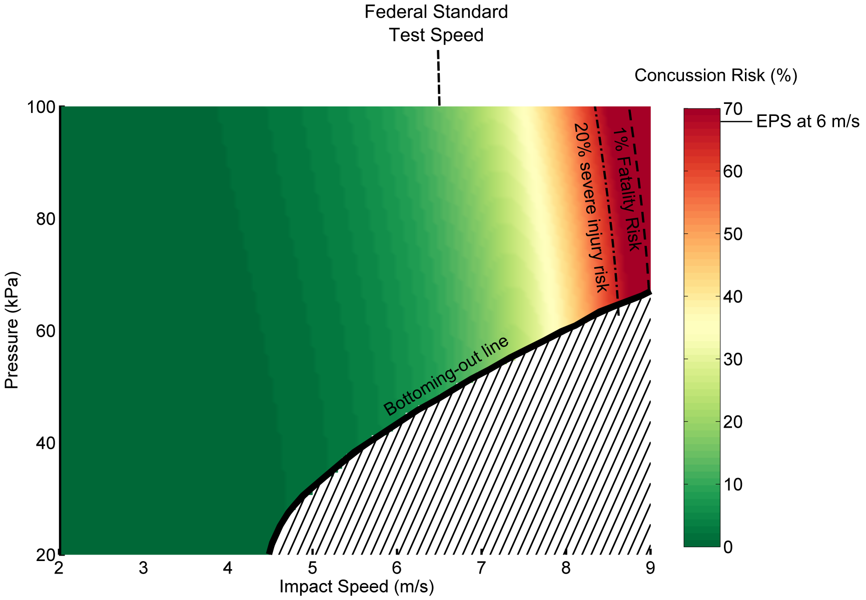


Figure 6. Optimization of an expandable helmet design: An optimum design scheme to minimize HIC values for the airbag theoretical model a fixed size of 12 cm, shown along with concussion risk values (AIS 2+) for varying impact velocities. 20% skull fracture (AIS 4+) and 2% fatality (AIS 6+) contour lines are also depicted. Hatched zone corresponds to bottom-out.

dynamics on the mechanical response of brain tissue.

Although this study is a first attempt to optimize the design of expandable helmets, there are a number of practical challenges that need to be addressed before these helmets can become widely accepted. For instance, these helmets can not be sold in US market currently since standards to test these types of helmets do not presently exist. Current evaluations of the effectiveness of bicycle helmets rely on simplified mechanical testing or the analysis of aggregated accident statistics along with other tests such as conditioning environments (temperature tests, water immersion), positional stability and dynamics strength of detention system. It is questionable whether expandable helmets would be able to pass some of these tests, *e.g.*, positional stability during inflation and/or impact tests on sharp anvils.

Another important issue regarding the real-life implementation of expandable helmets remains to be the underlying triggering . MEMS sensors need to detect an accident scenario accurately both for false positives (since at deploying airbag in an unwarranted situation could be dangerous itself) and false negatives (since in such cases there is an accident in the absence of proper protection). The triggering will also be needed to be tested and appropriate standards will need to be determined. This will be a critical challenge for the expandable helmets before they are widely accepted and confidently worn among bicycle riders.

CONCLUSIONS

Conventional helmet padding technology suffers from the practical limitation of a maximum wearable size. In this study, we optimized the size and the initial pressure values of an airbag helmet for varying head impact velocities and found that an airbag helmet with 0.12 m thickness at 70 kPa pressure reduces the risk of concussion below 10% (at 6.6 m/s head impact velocity which is the federal standard), severe head injury risks below 20% and fatality risks below 2% (at 9 m/s head impact velocity). The results show the potential of airbag helmets at reducing injury risk for cyclists and the inadequacies of the current helmet technology. However, before this technology becomes widely available, airbag helmets need more reliable impact triggering technologies and should be evaluated in more realistic bicycle accident simulations.

Acknowledgments

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Disclosure Statement

No competing financial interests exist.

References

[1] Baker, S. P. and O'neill, B. (1976). The injury severity score: an update. *Journal of Trauma and Acute Care Surgery*, 16(11):882–885.

[2] Bambach, M. R., Mitchell, R., Grzebieta, R. H., and Olivier, J. (2013). The effectiveness of helmets in bicycle collisions with motor vehicles: A case–control study. *Accident Analysis & Prevention*, 53:78–88.

[3] Bourdet, N., Deck, C., Carreira, R. P., and Willinger, R. (2012). Head impact conditions in the case of cyclist falls. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 226(3-4):282–289.

[4] Camarillo, D., Shull, P., and Mattson, J. (2013). An instrumented mouthguard for measuring linear and angular head impact kinematics in American football. *Annals of biomedical engineering . . .* , 41(9):1939–1949.

[5] Cheng, Z., Pilkey, W., Crandall, J., Bass, C., and Darvish, K. (1999). Limiting Performance of Helmets for the Prevention of Head Injury. *Shock and Vibration*, 6(5-6):299–320.

[6] Cripton, P. A., Dressler, D. M., Stuart, C. A., Dennison, C. R., and Richards, D. (2014). Bicycle helmets are highly effective at preventing head injury during head impact: Head-form accelerations and injury criteria for helmeted and unhelmeted impacts. *Accident Analysis & Prevention*, 70:1–7.

[7] Croop, B., Lobo, H., and DatapointLabs, N. (2009). Selecting material models for the simulation of foams in ls-dyna. In *Proceedings of the 7th European LS-DYNA conference, Dynamore Gmbh, Salzburg, Germany*.

[8] Curnow, W. J. (2003). The efficacy of bicycle helmets against brain injury. *Accident Analysis & Prevention*, 35(2):287–292.

[9] de Geus, B., Vandenbulcke, G., Int Panis, L., Thomas, I., Degraeuwe, B., Cumps, E., Aertsens, J., Torfs, R., and Meeusen, R. (2012). A prospective cohort study on minor accidents involving commuter cyclists in Belgium. *Accident; analysis and prevention*, 45:683–93.

[10] De Vries, D. (2009). Characterization of polymeric foams. *Eindhoven University of Technology*.

[11] Depreitere, B., Van Lierde, C., Maene, S., Plets, C., Vander Sloten, J., Van Audekercke, R., Van der Perre, G., and Goffin, J. (2004). Bicycle-related head injury: a study of 86 cases. *Accident; analysis and prevention*, 36(4):561–7.

[12] Do, S. and Weck, O. D. (2012). A personal airbag system for the Orion Crew Exploration Vehicle. *Acta Astronautica*, 81:239–255.

[13] Eilert-Petersson, E. and Schelp, L. (1997). An epidemiological study of bicycle-related injuries. *Accident Analysis & Prevention*, 29(3):363–372.

[14] Esgar, J. B. and Morgan, W. C. (1960). Analytical study of soft landings on gas-filled bags. *NASA*, (19980223608).

[15] Faul, M., Xu, L., Wald, M. M., and Coronado, V. (2010). Traumatic brain injury in the united states. *Atlanta, GA: Centers for Disease Control and Prevention, National Center for Injury Prevention and Control*.

[16] Federal Motor Vehicle Safety Standards (FMVSS) (2014). 571.202a. Section 571, Standard 202a - Head restraints.

[17] Finnoff, J. T., Laskowski, E. R., Altman, K. L., and Diehl, N. N. (2001). Barriers to bicycle helmet use. *Pediatrics*, 108(1):e4–e4.

[18] Folksam (2015). Bicycle Helmet Test. Technical report.

[19] Hansen, K., Dau, N., Feist, F., Deck, C., Willinger, R., Madey, S. M., and Bottlang, M. (2013). Angular impact mitigation system for bicycle helmets to reduce head acceleration and risk of traumatic brain injury. *Accident Analysis & Prevention*, 59:109–117.

[20] Healy, D. G. (2015). Head injuries in sport. *ABC of Sports and Exercise Medicine*, page 10.

[21] Hernandez, F., Wu, L. C., Yip, M. C., Laksari, K., Hoffman, A. R., Lopez, J. R., Grant, G. A., Kleiven, S., and Camarillo, D. B. (2014). Six degree-of-freedom measurements of human mild traumatic brain injury. *Annals of biomedical engineering*, pages 1–17.

[22] Hertz, E. (1993). A note on the head injury criterion (hic) as a predictor of the risk of skull fracture. In *Proceedings: Association for the Advancement of Automotive Medicine Annual Conference*, volume 37, pages 303–312. Association for the Advancement of Automotive Medicine.

[23] Howland, J., Sargent, J., Weitzman, M., Mangione, T., Ebert, R., Mauceri, M., and Bond, M. (1989). Barriers to bicycle helmet use among children: results of focus groups with fourth, fifth, and sixth graders. *American Journal of Diseases of Children*, 143(6):741–744.

[24] Juhra, C., Wieskötter, B., Chu, K., Trost, L., Weiss, U., Messerschmidt, M., Malczyk, A., Heckwolf, M., and Raschke, M. (2012). Bicycle accidents–do we only see the tip of the iceberg?: A prospective multi-centre study in a large german city combining medical and police data. *Injury*, 43(12):2026–2034.

[25] Kleiven, S. (2013). Why most traumatic brain injuries are not caused by linear acceleration but skull fractures are. *Frontiers in bioengineering and biotechnology*, 1.

[26] Lamb, L. and Hoshizaki, T. (2009). Deformation mechanisms and impact attenuation characteristics of thin-walled collapsible air chambers used in head protection. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of engineering in medicine*, 223(8):1021–1031.

[27] Maimaris, C., Summer, C., Browning, C., and Palmer, C. (1994). Injury patterns in cyclists attending an accident and emergency department: a comparison of helmet wearers and non-wearers. *Bmj*, 308(6943):1537–1540.

[28] Marieb, E. N. and Hoehn, K. (2007). *Human anatomy & physiology*. Pearson Education.

[29] Mertz, H. J., Prasad, P., and Irwin, A. L. (1997). Injury risk curves for children and adults in frontal and rear collisions. Technical report, SAE Technical Paper.

[30] Mills, N. and Gilchrist, A. (2008). Finite-element analysis of bicycle helmet oblique impacts. *International Journal of Impact Engineering*, 35(9):1087–1101.

[31] Mills, N. J. and Gilchrist, A. (2006). Bicycle helmet design. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 220(4):167–180.

[32] Moss, W. C. and King., M. J. (2011). Impact response of US Army and National Football League helmet pad systems. Technical report.

[33] Moss, W. C., King, M. J., and Blackman, E. G. (2009). Skull flexure from blast waves: a mechanism for brain injury with implications for helmet design. *Physical review letters*, 103(10):108702.

[34] Moss, W. C., King, M. J., and Blackman, E. G. (2014). Towards reducing impact-induced brain injury: lessons from a computational study of army and football helmet pads. *Computer methods in biomechanics and biomedical engineering*, 17(11):1173–1184.

[35] Nagurka, M. and Huang, S. (2004). A mass-spring-damper model of a bouncing ball. In *American Control Conference, 2004. Proceedings of the 2004*, volume 1, pages 499–504. IEEE.

[36] Newman, J. A. (1980). Head Injury Criteria in Automotive Crash Testing.

[37] Newman, J. A. (2002). Biomechanics of head trauma: head protection. In *Accidental injury*, pages 303–323. Springer.

[38] Newman, J. A., Shewchenko, N., and Welbourne, E. (2000). A proposed new biomechanical head injury assessment function-the maximum power index. *Stapp car crash journal*, 44:215–247.

[39] Ogden, R. (1972). Large deformation isotropic elasticity-on the correlation of theory and experiment for incompressible rubberlike solids. In *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, volume 326, pages 565–584. The Royal Society.

[40] Ommaya, A. K. and Gennarelli, T. (1974). Cerebral concussion and traumatic unconsciousness. *Brain*, 97(1):633–654.

[41] Ozturk, U. E. and Anlas, G. (2011). Finite element analysis of expanded polystyrene foam under multiple compressive loading and unloading. *Materials and Design*, 32(2):773–780.

[42] Pellman, E. J., Viano, D. C., Tucker, A. M., Casson, I. R., and Waeckerle, J. F. (2003). Concussion in professional football: reconstruction of game impacts and injuries. *Neurosurgery*, 53(4):799–814.

[43] Thompson, R. S., Rivara, F. P., and Thompson, D. C. (1989). A case-control study of the effectiveness of bicycle safety helmets. *New England journal of medicine*, 320(21):1361–1367.

[44] United States Consumer Product Safety Commision (CPSC) (1998). Safety Standard for Bicycle Helmets: Final Rule. Technical report.

[45] United States Consumer Product Safety Commision (CPSC) (2003). Head Injury-Related Deaths to Children Under 15 Years Old, Calendar Years, 1991-2000. Technical report.

[46] Zhang, L., Yang, K. H., and King, A. I. (2004). A Proposed Injury Threshold for Mild Traumatic Brain Injury. *Journal of Biomechanical Engineering*, 126(2):226–236.

APPENDIX

Helmet Impact Dynamics Modeling

The geometry we assume for the helmets is hemispherical shells, as shown in Figure 7. In making the analysis, the following general assumptions are made for helmet dynamics: 1) The head and the helmet are coupled rigidly. 2) The head & helmet system is only moving in the vertical direction. 3) The normal vector of the contact area is always in the impact direction.

Airbag Impact Dynamics Modeling

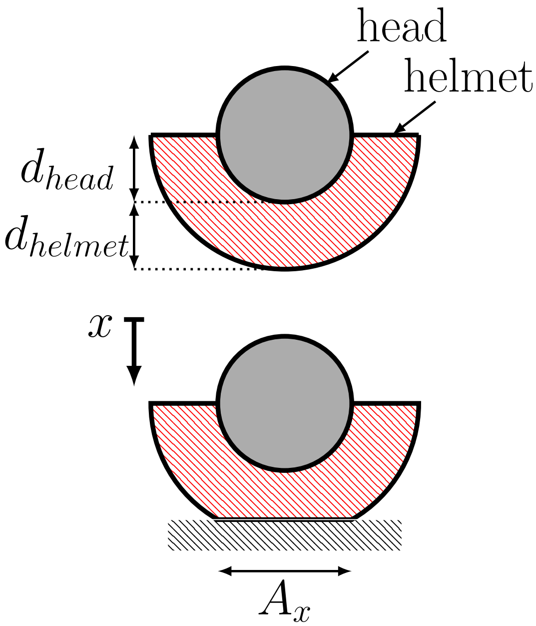

Figure 7. Contact geometry of helmet impact dynamics: Hemispherical shell models were assumed to model airbag and EPS helmets. The helmet is assumed to completely flatten out at deformation limit.

In modeling the airbag impact dynamics, the following assumptons are made: 1) Air behaves like an ideal gas at the given conditions. 2) The airbag is flexible but inelastic. 3) Friction and the bending resistance of the airbag fabric are neglected. 4) The mass of the air is negligible. The most general form of the equations of motion for a hemispherical airbag helmet is as follows:

$$m\ddot{x} + (P(x) - P_{atm})\ A\ (x) = mg \tag{1}$$

where x represents the instanteous distance between the center of gravity (CoG) of the head and the ground, m is the total system mass, $P(x)$ and $A(x)$ are instantenous pressure and contact area values of the airbag and P_{atm} is atmospheric pressure. The physical constraint to the system depicted in (1) is

$$d_{helmet} < x < d_{helmet} + d_{head} \tag{2}$$

where d_{head} is the vertical distance of the CoG of the head to the helmet and d_{helmet} is the thickness of the helmet.

We assume a hemispherical geometry for the airbag helmet. We assume that the helmet would completely flatten out if it reached to the deformation limit. This indeed can not happen for Figure 7 since the deformation is limited up to the skull. By using simple geometric relations, the contact area of the airbag helmet can be formulated as follows:

$$A(x) = \pi(d_{helmet} + d_{head})^2 \left[1 - \left(\frac{x}{d_{helmet} + d_{head}}\right)^2\right] \tag{3}$$

The initial volume of the airbag helmet is

$$V_i = \frac{2}{3}\pi(d_{helmet} + d_{head})^3 - \frac{2}{3}\pi {d_{head}}^3 \tag{4}$$

Using (3) and (4), we find the instantenous volume of the airbag as a function of x

$$V(x) = \pi(d_{helmet} + d_{head})^3 \left[\frac{x}{d_{helmet} + d_{head}} - \frac{1}{3}\left(\frac{x}{d_{helmet} + d_{head}}\right)^3\right] - \frac{2}{3}\pi {d_{head}}^3 \tag{5}$$

By using the assumption of ideal gas, we can find the instantenous pressure of the airbag helmet during the impact by simply equating $P(x)V(x)$ with $PiVi$ (initial conditions)

$$P(x) = P_i\left(\frac{V_i}{V}\right) \tag{6}$$

EPS Helmet Impact Dynamics Modeling

To model the impact dynamics of EPS helmets, we assume the same hemispherical shell geometry. The contact area of the EPS helmet is assumed to be of the form given in (3). The equation of motion for the EPS helmet is as follows:

$$m\ddot{x} + c_{EPS}\dot{x} + \sigma_{EPS}(\frac{x}{d_{helmet}})A\ \ (x) = mg \tag{7}$$

where x represents the instantaneous distance between the center of gravity (CoG) of the head and the ground, m is the total system mass, $\sigma_{EPS}(\frac{x}{d_{helmet}})$ is the loading/unloading stress-strain curve depicted in Figure 2A and $A(x)$ is the instantenous contact area between the EPS helmet and the ground. The effective damping coefficient c_{EPS} was calculated by using relations for a bouncing elastic body on a rigid surface[35]:

$$c_{EPS} = -\frac{2m}{\Delta T}\ln\varepsilon \tag{8}$$

where m is the total system mass, ΔT represents the contact duration and ε corresponds to coefficient of restitution. In order to find c_{EPS} , we need to solve for the coefficient of restitution, which is an implicit function of ΔT as follows

$$\Delta T = \pi\varepsilon^n\sqrt{\frac{h_0}{g}\left(1 + \frac{\ln\varepsilon}{\pi}\right)} \tag{9}$$

where n is the number of bounces that the elastic body experiences and h_0 is the height from which the head is dropped. We assume n to be 2 and ΔT to be 10 ms based on our experimental observations.

Summary of helmet dynamics parameters

We give an overview of the values of mass, helmet size and other critical parameters used for modeling helmet dynamics. Note that mass values of the system for PMHS and ATD experiments differ slightly.

Table 1. Summary of parameters used to model helmet dynamics

m_{PMHS} (kg)	m_{ATD} (kg)	d_{head} (m)$^?$	$d_{Hovding}$ (m)	d_{EPS}(m)	ΔT (ms)	n
4.21	4.54	0.112	0.12	0.025	10	2

Ogden material modeling

We use Ogden rubber material model that is widely used for modeling foams[39]. Assuming a zero lateral stress and zero Poisson's ratio, we can formulate the material stress as follows

$$\sigma = \frac{2}{\lambda}\sum_{i=1}^{N}\frac{\mu_i}{\alpha_i^2}\left(\lambda^{\alpha_i} - \lambda^{-\alpha_i\beta_i}\right) \tag{10}$$

where λ is defined as the stretch ratio (*i.e.*, the ratio between the final helmet thickness to the initial helmet thickness) and α, β and μ are material constants.

We use the first order approximation of (10) to model polymeric foams. The equation reduces to the following form

$$\sigma = \frac{2}{\lambda}\frac{\mu}{\alpha}\left(\lambda^{\alpha} - \lambda^{-\alpha\beta}\right) \tag{11}$$

For EPS20, the Ogden material parameters are given below in the table for the first-order approximation.

Table 2. Ogden parameters for EPS foam[7]

N	μ (kPa)	α	β
1	44.2	21.5	0

For ideal foam optimization in Figure 5A, the limits we used for the above parameters are as follows

$$\mu = [0, 100]kPa, \alpha = [0, \infty], \beta = [0, 1] \tag{12}$$

These limits lead to a semi-constrained optimization and give the opportunity to minimize peak accelerations at varying helmet sizes, as shown in Figure 5A.

Bicycle helmet test
2015
by Folksam

Folksam

This is why we test bicycle helmets

Every day three cyclists in Sweden sustain head injuries, which are some of the most severe injuries a cyclist can experience. Data from real-life crashes show that bicycle helmets are very effective to reduce injuries. Two out of three head injuries from bicycle accidents could have been avoided if the cyclist had worn a helmet.

We are committed to what is important to our customers and to you. When we test and recommend safe bicycle helmets we believe this can help to make your life safer and we provide tips on how to prevent injury.

How does a bicycle helmet obtain our good choice label?

Helmets which obtain the best overall results in the bicycle helmet test by Folksam are given our good choice label. The good choice symbol may only be used by products which have obtained the best scores in one of our tests.

Helena Stigson

Helena Stigson, PhD
Associate Professor
Traffic Safety Research

Read more at folksam.se/cykel

Folksam

Summary

Folksam has tested 18 bicycle helmets on the Swedish market for teenagers and adults. All helmets included in the test have previously been tested and approved according to the CE standard, which means that the energy absorption of the helmets has been tested with a perpendicular impact to the helmet. This does not fully reflect the scenario in a bicycle crash. In a single-bicycle crash or in collision with a motor vehicle, the impact to the head will be oblique towards the ground or the car. The intention was to simulate this in the tests since it is known that angular acceleration is the dominating cause of brain injuries.

In total four separate tests were conducted: a test to evaluate the shock absorption of the helmets and three tests to evaluate the helmets' protective capacity in cycle crashes with varying impact angles; an oblique impact to the upper part of the helmet, an oblique impact against the side of the helmet and an oblique to the rear part of the helmet. Computer simulations were also conducted for all oblique impact directions to evaluate the risk of injury. In these simulations an FE model of the brain developed by researchers at the Royal Institute of Technology (KTH) was used. Since the FE model is based on the brain's tolerance levels, the simulation output was used to compare and rate the helmets.

In total five helmets obtained the Folksam good choice label: Bell Stoker MIPS, Giro Savant MIPS, Hövding 2.0, POC Octal AVIP MIPS and Spectra Urbana MIPS. The Hövding 2.0 head protector, which protects the head with an airbag in the event of an accident, showed the overall best result. The conventional bicycle helmets Bell Stoker MIPS, Giro Savant MIPS, POC Octal AVIP MIPS and Spectra Urbana MIPS, which are all fitted with MIPS (Multi-directional Impact Protection System), also showed good test results. In general helmets fitted with the MIPS reduced the rotational energy better than other conventional helmets without the system. However, there is no guarantee that a helmet with the MIPS is good. Two helmets, Giro Sutton MIPS and Scott Stego MIPS, showed lower protection than the average good helmet even though these were equipped with rotational protection.

Folksam's tests show that bicycle helmets need to absorb energy more effectively. The helmet safety standard of today is no guarantee for a high helmet safety level. Our study shows that a conventional helmet that meets today´s standards does not prevent from getting a concussion in case of an accident. The EU helmet standard limits the acceleration to the head to be under 250g. This level corresponds to a 40 % risk of skull fractures. Based on the shock absorption test, all helmets except from five (Abus S-Force Peak Official Vasalopp-helmet, Carrera Foldable, Giro Sutton MIPS, Occano Urban Helmet and Yakkay) showed a linear acceleration lower than 180 g, which corresponds to a 5 % risk of skull fractures. The Hövding 2.0 helmet performed almost three times better than all the other conventional helmets (48 g vs. other helmets that were around 175 g). The most important is that this helmet also reduced the rotational energy to the head better than conventional helmets. In the oblique impact tests helmets equipped with MIPS preformed better than helmets without the system. The difference was higher in the oblique impact with contact point on the upper part of the helmet (y-rotation) and contact point on the side of the helmet (x-rotation) than in the oblique impact with contact point on the back side of the helmet (z-rotation). All helmets need to more effectively reduce rotational energy.

The greatest difference between a good and a bad helmet is how well it protects the head during oblique impacts. To prevent helmets from being sold without rotational protection the legal requirements should also include such oblique impacts. Since 2012 Folksam has conducted helmet

tests to help consumers to choose a safe helmet and to encourage helmet manufacturers to design safer helmets. The proportion of helmets with rotational protection has increased significantly during this period, which shows that consumer tests are important in driving development forwards.

Background

Every day three cyclists in Sweden sustain head injuries, which are some of the most severe injuries a cyclist can experience[1]. Over 70 percent of the head injuries occur in single-bicycle crashes. However, generally head injuries are more severe in crashes involving motor vehicles than in single bicycle crashes. Data from real-life crashes show that bicycle helmets are very effective in reducing head injuries. Two out of three head injuries from bicycle accidents could have been avoided if the bicyclist had worn a helmet (Rizzi et al, 2013). In the event of more severe brain injuries the protective effect is even higher (Thompson et al, 2009). Real-life data indicate that the most common impacts to the head are impacts against the temple or the back of the head (Björnstig et al, 1992). Oblique impacts result in rotation of the head, to which the brain is most sensitive to (Margulies and Thibault, 1992).

In the current certification tests in which the helmet is dropped straight onto a flat anvil and onto a kerbstone anvil only the energy absorption in a perpendicular impact is evaluated. An approved helmet should comply with the 250 g limit (Swedish standard SS-A 1078, 1997). The acceleration which the head form is exposed to must therefore be less than 250 g, a limit that corresponds to a 40% risk of a skull fracture. According to Zhang et al (2004) concussion with or without loss of consciousness can occur at approximately 60-100 g. Researchers (Marguelies and Thibault, 1992, Kleiven, 2007) have also shown that the brain is much more sensitive to rotational movement than to linear forces. The risk of concussion or more serious injuries such as Diffuse Axonal Injury (DAI), bleeding or contusion are caused by the rotational acceleration and/or the rotational velocity (Gennarelli et al, 1987, Holbourn, 1943, Löwenhielm, 1975). Despite this, translational acceleration is widely used today to optimise helmets and safety systems in the automotive industry.

Objective

Folksam’s bicycle helmet test is intended to evaluate the energy absorption of current helmets both regarding perpendicular impacts and oblique impacts against the head in order to cover different injury-generating accident scenarios better than the legal requirements. This is to provide consumers and shop owners with better data when choosing bicycle helmets. In addition, we hope to be able to encourage helmet manufacturers to make better helmets as a result of Folksam’s tests.

Method

A total of 18 bicycle helmets have been included in the test; Table 1. When choosing helmets, we looked at the range available in bicycle/sports shops and web shops. This was in order to choose the helmets most readily available on the Swedish market, but also to choose models with special protective features.

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[1] Based on data from STRADA [Swedish Traffic Accident Data Acquisition] which contains hospital records of road crashes in Sweden, year 2014

***Table 1**. Helmets included in the study*

Cycle helmets 2015	Type of helmet	Price (SEK)
Abus S-Force Peak Official Vasaloppet Helmet	Classic	700-900
Bell Stoker MIPS*	MTB	1000-1400
Biltema cycle helmet	Classic	100
Carrera Foldable	Classic	700-900
Casco Active-TC	Classic	700
Giro Savant MIPS*	Classic	1000-1300
Giro Sutton MIPS*	Skate	1000
Hövding 2.0	Collar	2700
Limar Ultralight	Classic	1200-1500
Melon Urban Active	Skate	600
Occano U MIPS Helmet	Classic	500
Occano Urban Helmet	Classic	350
POC Octal	Classic	2700
POC Octal AVIP MIPS*	Classic	3500
Scott Stego MIPS*	MTB	1700
Smith Forefront**	MTB	2000
Spectra Urbana MIPS*	Classic	650
YAKKAY with and without cover	Skate	600-700 + 400 cover

** The helmet is fitted with a MIPS system, an extra protection aimed at lowering rotational acceleration in the event of an oblique impact*

*** Smith Forefront is partly made of material with a honeycomb structure.*

Seven helmets, *Bell Stoker with MIPS, Giro Savant MIPS, Giro Sutton MIPS, Occano U MIPS Helmet, POC Octal AVIP MIPS, Scott Stego MIPS and Spectra Urbana MIPS, were equipped* a Multi-directional Impact Protection System (MIPS), which is intended to reduce the rotational acceleration of the brain caused by oblique head impacts. The protection is based on a low friction shell on the inside of the helmet that can slide on the inside of the helmet. The Smith Forefront helmet was selected because it is claimed to be extremely light and impact resistant since the material in the helmet is partly made up of a honeycomb structure[2]. The Yakkay helmet was selected since it is sold with a cover as additional equipment. The intention was to evaluate its effect on the test results. The skate helmet Melon Urban Active was selected because it was of a much lighter construction (up to 30% lighter) in comparison with other skate helmets, for which it was awarded the international bicycle industry prize Eurobike Award 2013. Skate helmets have generally performed worse in Folksam's previous helmet tests (Stigson et al, 2012, Stigson et al, 2013). Since the outer shell of Melon Urban Active is thinner the hypothesis was that it should therefore absorb more impact energy than the skate helmets tested previously. The Limar Ultralight helmet was selected since it was marketed as the world's lightest bicycle helmet. Folksam has already tested the Hövding head protector previously (Stigson et al, 2012).

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[2] Previous studies have shown that the honeycomb structure reduces the translational acceleration by 14% and the rotational acceleration by 34% (Hansen et al 2013)

At that time it was only possible to test the Hövding's energy absorption in the perpendicular impact procedure. In addition, the head protector is available in a new updated version, Hövding 2.0. In this year's test Folksam along with SP developed a test method in which it was also possible to test Hövding 2.0 in oblique impacts. All helmets in the test are CE marked in accordance with the European safety standard (Swedish standard SS-EN 1078, 1997) or Directive 89/686/EEC[3]. Helmets included in the test fall within a price range of SEK 100 to SEK 3500.

The four impact tests are designed to compare the potential of the helmets ability to absorb impact energy and to evaluate the protective effect of the helmets in bicycle crashes. The method used in Folksam helmet testing 2015 differs from our previous helmet tests (Stigson et al. 2012; Stigson et al. 2013; Stigson et al. 2014; Stigson et al. 2014). The test set-up has been modified to correlate with the proposal from some of the members in the CEN Working groups 11 "Rotational test methods" (CEN/TC158-WG11 2014; Willinger et al. 2014). In total four separate tests were conducted, Table 2 and Figure 1. The acceleration pulses measured from these tests have then been applied to a validated data-simulated model of the human brain (Kleiven, 2003, Kleiven, 2006b, Kleiven, 2007) to compare the helmets.

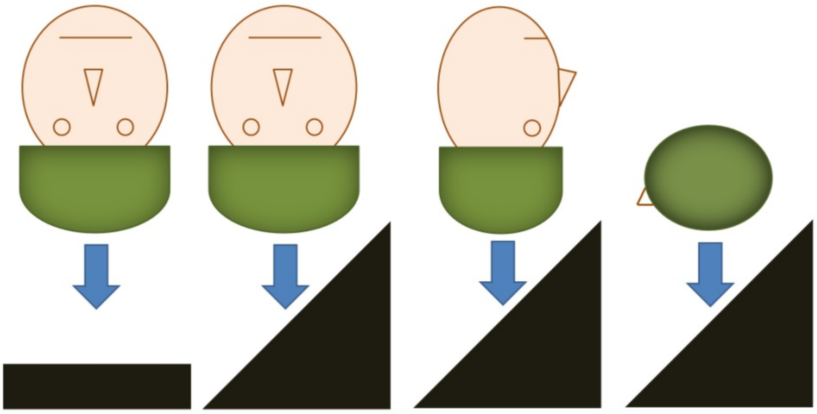

Figure 1. *Test from the left: 1) Shock Absorption 2) oblique impact to the side of the helmet 3) oblique impact to the upper part of the helmet 4) oblique impact to the rear part of the helmet*

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3 CE marking covers some thirty product areas such as toys and personal protective equipment. In order for a product to be approved, the product needs to comply with certain basic requirements. Either the product is tested according to one or more harmonised standards such as EN1078, which applies to bicycle helmets or the company engages a Notified Body (e.g. SP), which has to evaluate the product in relation to the basic requirements for CE marking. Then accreditation of independent technical experts takes place at an authority. In Sweden accreditation is carried out by SWEDAC (Swedish Board for Accreditation and Conformity Assessment). The test method for cycle helmets is limited in design terms since the current standard (EN 1078) is designed for conventional helmets and is unfortunately not applicable to Hövding since it requires a neck for support during the inflation phase. SP has developed the test method for evaluating the Hövding head protector and this method is accredited by SWEDAC.

Table 2. Included tests

Test	Velocity	Angle	Description
Shock Absorption	5.6 m/s	0°	The helmet was dropped from a height of 1.5 m to a horizontal surface in the same way as in the regulation test of shock absorption.
Oblique impact A. Contact point on the upper part of the helmet.	6 m/s	45°	A test that simulates an actual bicyclist-vehicle-crash or a single bicycle crash. Rotation around the x-axis.
Oblique impact B. Contact point on the side of the helmet.	6.0 m/s	45°	A test that simulates an actual cyclist-vehicle-crash or a single bicycle crash. Rotation around the y-axis.
Oblique impact C. Contact point on the side of the helmet.	6.0 m/s	45°	A test that simulates an actual cyclist-vehicle-crash or a single bicycle crash. Rotation around the z-axis.
Computer simulations	-	-	As input into the FE model, x, y and z rotation and translation acceleration data from the HIII head in the three tests above were used

Shock Absorption

The helmet was dropped from a height of 1.5 m to a horizontal surface according to the European standard (EN1078), which sets a maximum acceleration of 250g, Figure 2. The shock absorption test is the only partial test included in our test that is mandatory by law when testing helmets. The ISO head form was used and the test was performed with an impact speed of 5.42 m/s. The helmets were tested in a temperature of 15°C. The impact test was only performed in a helmet position in which the initial angle of the helmeted head was 0 degrees. The test was performed by SP, which is accredited for testing and certification in accordance with the bicycle helmet standard EN 1078.

Figure 2. *The method used in shock absorption test*

Three Oblique Tests

In three oblique tests the ISO head form was replaced by the Hybrid III 50th Male Dummy head, figure 3-4. The reason was that a Hybrid III 50th male dummy head has much more realistic inertial properties. The helmeted head was dropped against a 45° inclined anvil with a friction similar as asphalt. The impact velocity was 6.0 m/s.

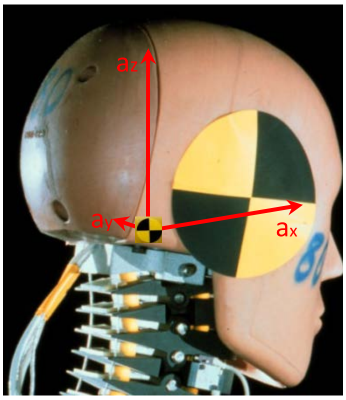


Figure 3. *Translational acceleration*

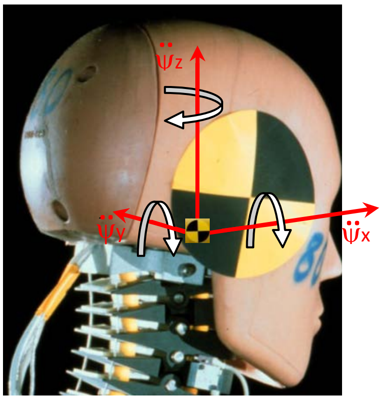


Figure 4. *Rotational acceleration*

The impact to the side of the helmet was located at parietal level and the impact was applied in the frontal plane, resulting in rotation around the X direction. The head was dropped 90° horizontally angled to the right resulting in a contact point on the side of the head, Figure 5. The impact to the upper part of the helmet resulted in rotation around the Y direction, Figure 6. This impact simulates a crash with oblique impact to the front of the head. The third impact was located at parietal level and was applied in the frontal plane, resulting in a rotation around the Z direction. The head was angled to the side which resulted a contact point on the side of the head, Figure 7. All three oblique tests were simulating a single-bicycle-crash or bicycle-to-car-crash with an oblique impact to the head.

Figure 5. *Oblique test with rotation around the x-axis.*

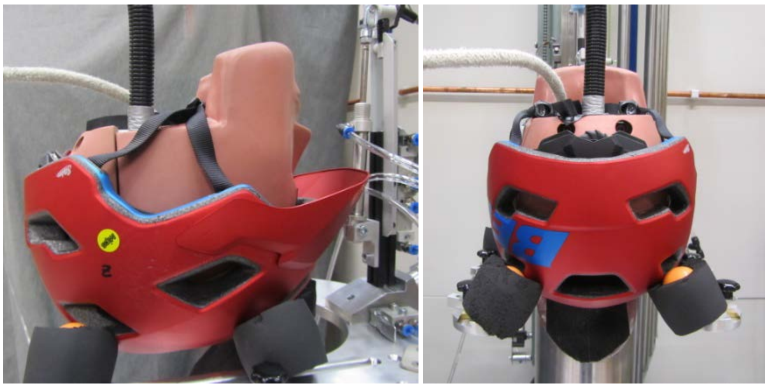


Figure 6. *Oblique test with rotation around the y-axis*

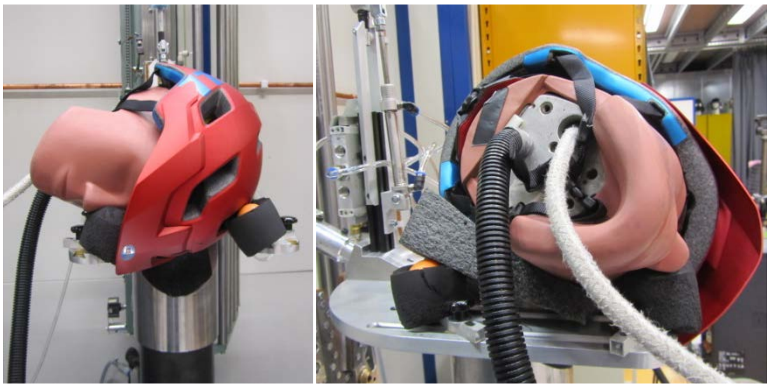


Figure 7. *Oblique test with rotation around the z-axis (head pre position: 20 ° in x and 35° in z)*

The Hövding 2.0 helmet

The test with the Hövding 2.0 was conducted in similar principles as the standard EN1078, *5.1 Shock Absorption*. However, in both the shock absorption test as well as in the three oblique tests, an anvil with larger dimensions was used, Figure 8. If Hövding 2.0 would have been tested against the anvil used for a conventional helmet it would have been a risk that it would get in contact with the edges of the anvil. The airbag of the Hövding 2.0 had a pressure of 0.55 bar.

Figure 8. *The Hövding2.0 and the larger anvil*

Computer simulations (FE model)

Computer simulations were conducted for all the three oblique impact tests. Table 3-5 shows the results from the simulations, which gave the brain tension ratio caused by rotation of the brain. The strain was between 6-44%. A strain above 26% corresponds to a 50% risk for concussion (Kleiven, S. and W.N. Hardy 2002, Margulies, S.S. and L.E. Thibault 1992).

The simulation was conducted by KTH (the Royal Institute of Technology) in Stockholm. As input into the FE model, x, y and z rotation and translational acceleration data from the HIII head were used. The FE model of the brain (Figure 9) which was used in the tests is described by Kleiven (2006 and 2007). The researchers at KTH did not know the brand and model of the helmets they were doing the

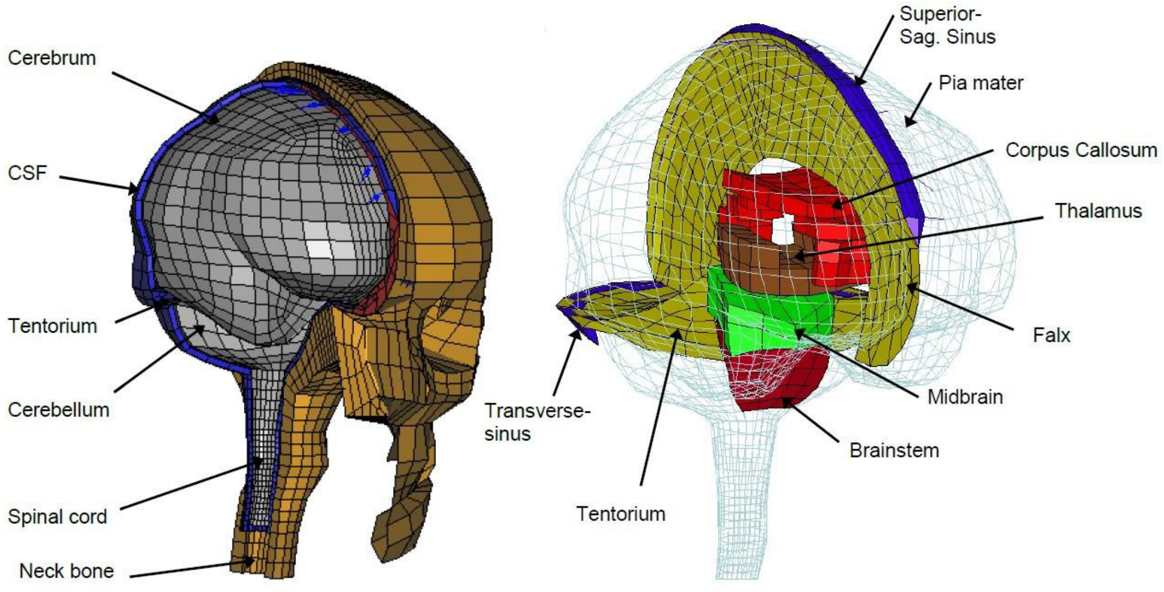


Figure 9. Finite element model of the human brain

Injury criteria

The mathematical model predicts a 50% risk of concussion in the event of strains of 26% in the grey matter of the brain. The simulation shows the maximum strain that occurs in the brain matter during each test, which in turn can be translated into a risk of injury.

Results

The results of four crash tests are reported below: a shock absorption test performed on a basis similar to that in the legal requirements, and three oblique impacts.

Shock Absorption

All helmets in the shock absorption test showed accelerations lower than 250 g, Table 2. Five helmets (Abus S-Force Peak, Carrera Foldable, Giro Sutton MIPS, Occano Urban Helmet and Yakkay) got a linear acceleration lower than 180 g, which corresponds to a 5 % risk of skull fracture (Mertz et al. 1997). The Hövding 2.0 helmet performed almost three times better than all the other conventional helmets (48 g vs other helmets that were around 175 g). The POC Octal performed best and Yakkay preformed worst of the conventional helmets.

Table 2. *Shock Absorption - Linear acceleration*

Manufacturer	Translational acceleration (g)
Abus S-Force Peak Official Vasaloppet	202
Bell Stoker MIPS	155
Biltema cycle helmet	189
Carrera Foldable	225
Casco Active-TC	170
Giro Savant MIPS	153
Giro Sutton MIPS	212
Hövding 2.0	48
Limar Ultralight	169
Melon Urban Active	173
Occano U MIPS Helmet	178
Occano Urban Helmet	192
POC Octal AVIP MIPS	140
POC Octal	135
Scott Stego MIPS	166
Smith Forefront	231
Spectra Urbana MIPS	168
YAKKAY with cover	242
Average/Median	**175/172**

Oblique Test – rotation around the x-axis

In the test, which reflects the helmet's protective effectiveness in a bicycle crash with oblique impact to the side of helmet (rotation around the x-axis), the translational accelerations were in average 129 g, which is considerably lower than the threshold for the current helmet standard (250 g), Table 3 and Appendix A. The lowest translational acceleration was measured in Hövding 2.0 (42 g), and the highest value was measured in tests of Carrera Foldable (180 g). The mean value of the rotational accelerations was 6,406 rad/s^2. The lowest rotational acceleration was measured in Hövding 2.0 (1,546 rad/s^2). The mean rotational velocity was 27.5 rad/s. The maximum value was measured in Scott Stego MIPS (35.4 radians/s) and the lowest value was measured in Hövding (24.3 rad/s). When simulations were conducted, the strain in the grey matter of the brain varied from 6% to 22%. All the values measured were below the limit for a 50% risk of concussion (26% strain). The lowest strain was measured when testing the Hövding 2.0 head protector. The illustrations below show the point at which the maximum strain in the brain is measured when testing the best or worst conventional bicycle helmets and the Hövding 2.0; Figure 10 and Figure 11. The protective potential of the helmets has been ranked based on the strain calculated from the FE model, which is presented in Table 4.

Table 3. *Oblique test 1 (rotation x)*

Helmet	Tran. acceleration (g)	Rot. acceleration (krad/s^2)	Rot. velocity (rad/s)	Strain (%)
Abus S-Force Peak Official Vasalopp's Helmet	175	7.5	29.9	16
Bell Stoker MIPS	112	4.2	23.2	11
Biltema cycle helmet	124	5.1	29.3	15
Carrera Foldable	180	7.9	27.6	16
Casco Active-TC	123	7.8	31.3	20
Giro Savant MIPS	120	5.3	24.7	12
Giro Sutton MIPS	124	4.5	23.8	11
Hövding 2.0	42	1.5	26.9	6
Limar Ultralight	132	8.5	31.5	18
Melon Urban Active	138	6.1	29.2	16
Occano U MIPS Helmet	121	5.1	23.9	12
Occano Urban Helmet	161	7.5	31.6	17
POC Octal	102	7.6	32.2	19
POC Octal AVIP MIPS	95	5.3	23.2	12
Scott Stego MIPS	94	6.8	35.4	19
Smith Forefront	136	8.1	31.5	18
Spectra Urbana MIPS	155	6.1	21.9	12
YAKKAY with cover	150	5.8	19.2	14
YAKKAY without cover	174	10.8	33.8	22
Average/Median	**129/124**	**6.4/6.1**	**27.5/29.2**	**15/16**

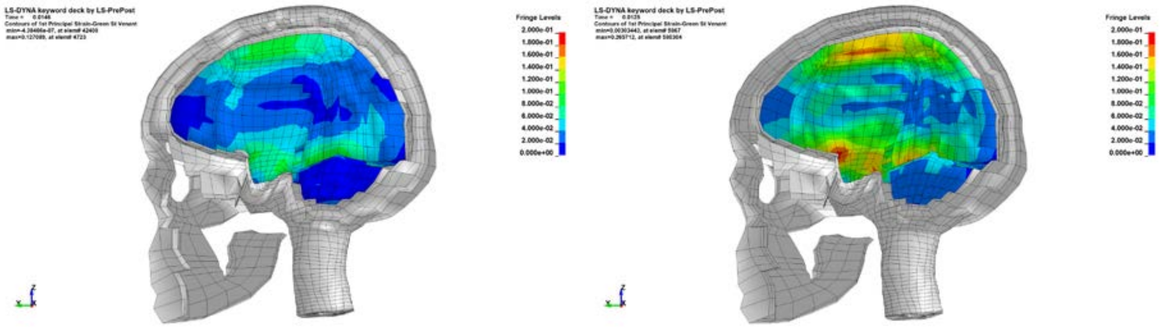


Figure 10. *Maximuml strain in the brain, rotation in x – impact to the side of the helmet. To the left one of the best and to the right one of the worst outcomes.*

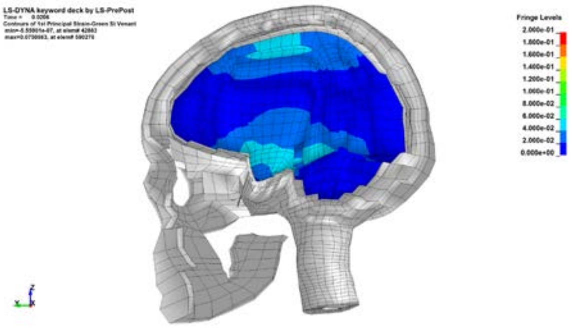


Figure 11. *Maximum strain in the brain,. rotation in the xaxis - Hövding 2.0*

Oblique Test – rotation around the Y-axis

In the test that reflects the helmet's protective effectiveness in a bicycle crash with an oblique impact to the upper part of helmet (rotation around the y-axis), the translational accelerations was in average 119 g, which is considerably lower than the threshold for the current helmet standard (250 g), Table 4. The minimum translational acceleration was measured in Hövding 2.0 (37 g), and the highest value was measured in tests of YAKKAY (174 g). The mean value of the rotational accelerations was 12.854 rad/s^2. The lowest rotational acceleration was measured in Hövding 2.0 (1.735 rad/s^2). The mean rotational velocity was 33.1 rad/s. The maximum value was measured in YAKKAY without a cover (39.4 rad/s), and the lowest value was measured in Hövding (24.3 rad/s). When simulations were conducted the maximum strain in the brain matter varied from 7 to 35%; Table 5 and Appendix A. The lowest strain was measured in the Hövding 2.0. Among the conventional helmets the lowest strain was measured when testing the YAKKAY helmet with cover and the highest strain was measured in the YAKKAY without cover. In six tests (Casco Active-TC, Limar Ultralight, Melon Urban Active, Smith Forefront and YAKKAY without cover) values which are above the 26% limit were measured, which corresponds to a 50% risk of concussion in those regions in the grey matter of the brain where the highest strain was measured (Kleiven. 200b. Kleiven. 2007). The illustrations below show the point at which the maximum strain in the brain is measured for the best and worst scoring helmets; Figure 12. There was a considerable difference between the strain in the helmets with the best and worst outcomes. The strain is shown from 0 (Blue) to 39%. The red areas in the illustration show the parts of the brain that run a 50% risk of concussion.

Table 4. *The values measured in an oblique impact on the upper part of the helmet (rotation around Y)*

Helmet	TRANS. ACC. [g]	ROT. ACC. [krad/s2]	ROT. VEL. [rad/s]	Strain (%)
Abus S-Force Peak Officiella Vasaloppshjälmen	131	7.2	33.4	23
Bell Stoker MIPS	100	6.2	31.8	23
Biltema cykelhjälm	115	7.1	36.4	25
Carrera Foldable	147	7.8	32.9	25
Casco Active-TC	116	8.0	38.8	29
Giro Savant MIPS	100	4.2	28.3	17
Giro Sutton MIPS	116	6.1	34.2	23
Hövding 2.0	37	1.7	28.6	7
Limar Ultralight	121	7.0	36.9	26
Melon Urban Active	131	8.2	34.5	26
Occano U MIPS Helmet	126	5.3	29.1	20
Occano Urban Helmet	121	7.6	35.8	27
POC Octal	90	6.2	35.6	24
POC Octal AVIP MIPS	87	4.5	30.5	19
Scott Stego MIPS	103	6.7	32.7	24
Smith Forefront	166	10.0	38.9	30
Spectra Urbana MIPS	115	5.8	27.2	19
YAKKAY with cover	156	5.1	24.3	16
YAKKAY without cover	174	12.9	39.4	35
Mean/Median	**119/116**	**6.7/6.7**	**33.1/33.4**	**23/24**

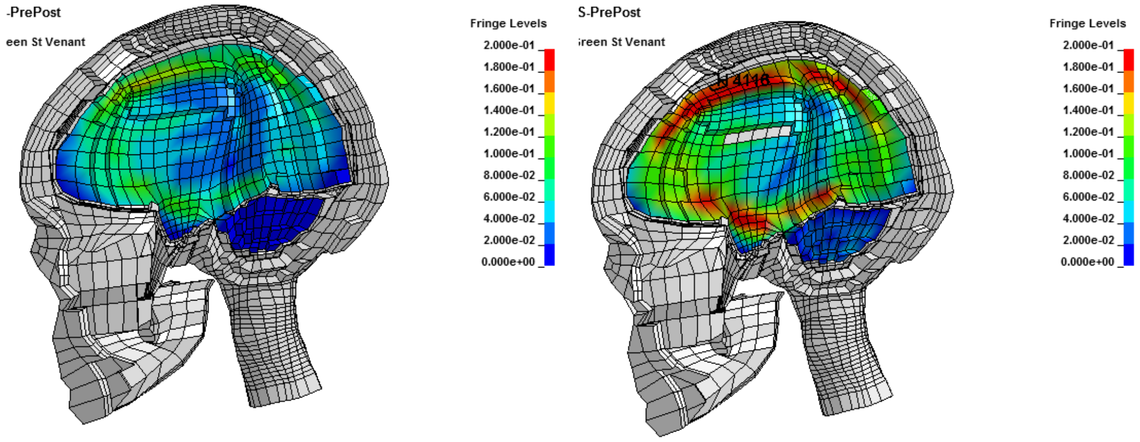


Figure 12. *The maximum strain in the brain. rotation in the y-axis. To the left the helmet with the lowest value and to the right the one with the highest value.*

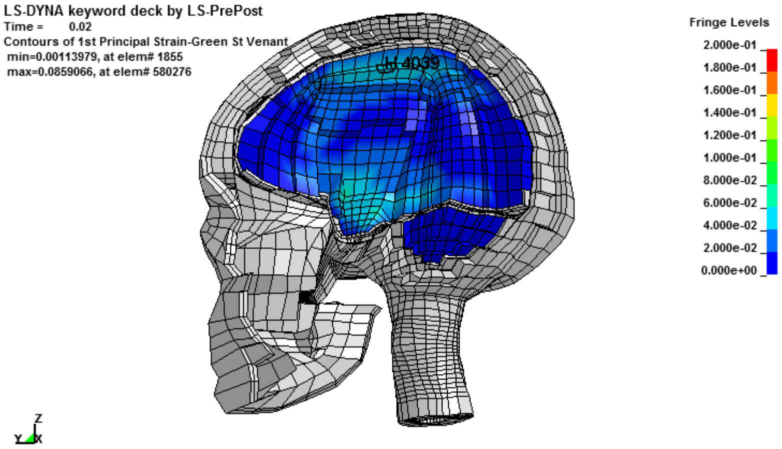


Figure 13. *Maximum strain in the brain, rotation in y - Hövding 2.0*

Oblique Test – rotation around the z-axis

In the test that reflects the helmet's protective effectiveness in a bicycle crash with oblique impact to the rear part of the helmet (rotation around the z-axis), the translational accelerations was in average 117 g, which is considerably lower than the threshold for the current helmet standard (250 g) . Table 5. The minimum translational acceleration was measured in Hövding 2.0 (27 g), and the highest value was measured in tests of YAKKAY (167 g). The mean value of the rotational accelerations was 12.042 rad/s^2. The lowest rotational acceleration was measured in Hövding 2.0 (2828 rad/s^2). The mean rotational velocity was 40.9 rad/s. The maximum value was measured in YAKKAY without a cover (46.6 rad/s), and the lowest value was measured in Hövding (33.7 rad/s) . When simulations were conducted the maximum strain in the brain varied from 31 to 44%; Table 6 and Appendix. When testing the Hövding 2.0 head protector a strain of 19% was measured, which is below the limit for a 50 % risk of a concussion, Figure 14-15.

Table 5. *The values measured in oblique impact on the rear part of the helmet (rotation around z)*

Helmet	TRANS. ACC. [g]	ROT. ACC. [krad/s2]	ROT. VEL. [rad/s]	Strain (%)
Abus S-Force Peak	145	14.4	39.5	33
Bell Stoker MIPS	114	10.5	39.1	31
Biltema cykelhjälm	126	13.8	42.1	34
Carrera Foldable	157	15.5	42.3	35
Casco Active-TC	76	10.1	44.4	35
Giro Savant MIPS	103	9.5	38.7	31
Giro Sutton MIPS	139	13.7	41.0	33
Hövding 2.0	27	2.8	37.1	19
Limar Ultralight	111	12.4	43.2	34
Melon Urban Active	128	12.6	40.5	33
Occano U MIPS Helmet	156	14.7	39.5	32
Occano Urban Helmet	131	13.9	42.6	35
POC Octal AVIP MIPS	77	9.2	43.5	33
POC Octal	74	10.2	42.1	33
Scott Stego MIPS	86	9.4	42.8	33
Smith Forefront	149	13.5	40.0	33
Spectra Urbana MIPS	109	10.5	40.2	32
YAKKAY with a cover	167	14.1	36.0	30
YAKKAY without a cover	142	18.1	46.6	44
Mean/Median	**117/126**	**12.0/12.6**	**40.9/41.0**	**33/33**

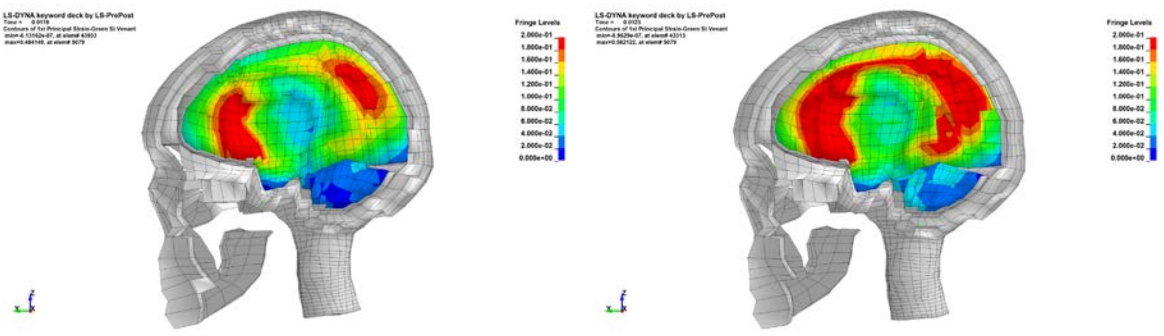


Figure 14. *The maximum strain in the brain. rotation in the zaxis. To the left the helmet with the lowest value and to the right the one with the highest value.*

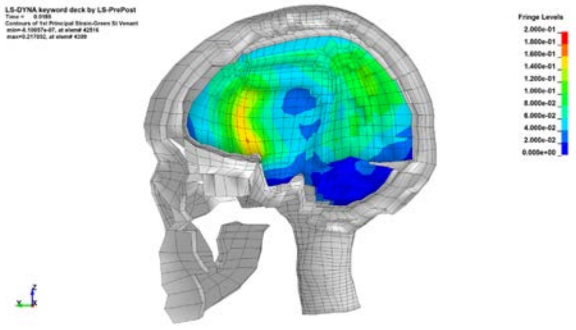


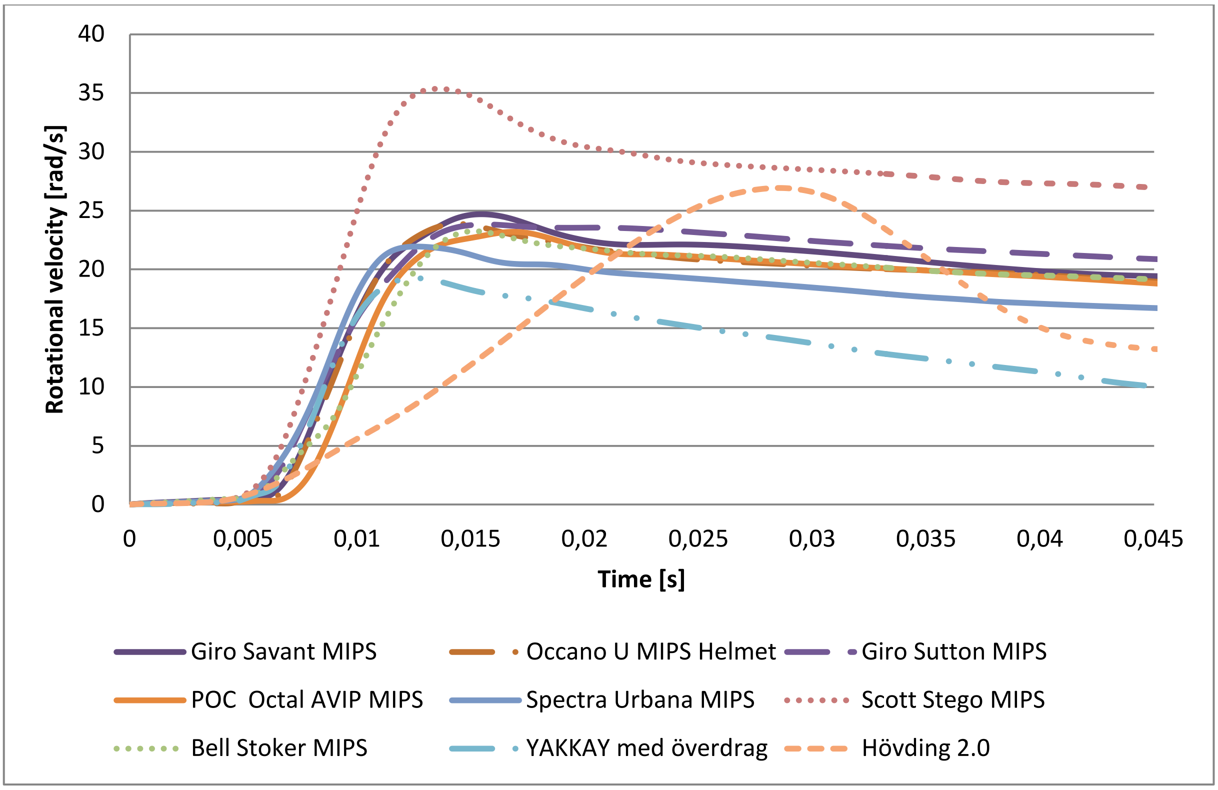
Figure 15. *Maximum strain in the brain, rotation in the z-axis - Hövding 2.0*

Discussion and conclusions

All the helmets included in the test comply with the legal requirements for a bicycle helmet. The legal requirements do not cover the helmets' capacity to reduce the rotational force. i.e. when the head is exposed to rotation due to the impact. The Folksam test shows a relatively large variation in the test comparing the helmets' capacity to absorb impact energy (48-242 g). Experience from American football indicates that head injuries start to occur at 60-100 g (Zhang et al 2004). In addition, the risk of skull fractures could be dramatically reduced (from a 40% to a 5% risk) if the translational acceleration would be reduced from 250 g to 180 g (Mertz et al. 1997). Helmets should therefore be designs to reduce the translational acceleration well below the legal requirement (250 g), provided that they also take into account the rotational forces to avoid brain injuries. The translational acceleration is mainly associated with the risk of skull fracture whereas the rotational acceleration and rotational velocity are associated with brain injuries. The results from the Folksam helmet test clearly show that it is possible to design a helmet that meets the legal requirements with a wide margin. The conventional helmet POC Octal reduced the energy that the head form was exposed to with almost half of the threshold of the requirements (135 g compared with 250 g). However, the Hövding 2.0., a head protector that is inflated during an accident situation and acts as an airbag for the head, obtained the best results. The translational acceleration was 48 g, a value almost 3 times better than the best conventional helmet, POC Octal. The tests indicate that the impact absorbing materials in today's helmets are far too stiff. In order to obtain lower head acceleration softer impact absorbing materials would be required, which probably need to be somewhat thicker (Mills and Gilchrist. 2006, Asiminei et al 2009, Fahlstedt. 2005). At the same time there are requirements to spread the force in connection with the legal requirement test against a kerbstone. A hard outer shell is required to meet this requirement simultaneously. By using different materials and concepts the helmets should be able to be more efficient to absorb the energy during a head impact. When developing a standard many different limits are set based on the assumed protective capacity of the existing materials. Most helmets have been of a similar design for a relatively long period and few improvements have been made even though new impact-absorbing materials have been developed. One of the helmets, Smith Forefront, is constructed with a honeycomb design. It has previously been shown that honeycomb design is effective in reducing both translational and rotational accelerations (Hansen et al. 2013). However, the Smith Forefront was too stiff and was shown to be one of those with the highest values measured.

Few helmets provide good protection against oblique impacts (rotational combined with translational acceleration), which is probably the most common accident scenario for a bicycle accident with a head impact. An oblique impact to the head means high risk of severe injury such as concussion with a loss of consciousness and diffuse axonal injury (DAI). Several of the helmets, Bell Stoker with MIPS, Giro Savant MIPS, Giro Sutton MIPS, Occano U MIPS Helmet, POC Octal AVIP MIPS, Scott Stego MIPS and Spectra Urbana MIPS, are designed to absorb rotational force. These helmets generally perform well in the rotation tests. However, the fact that a helmet has rotational protection is notany guarantee for a good protection. The tests clearly show a large variation between the 18 helmets and there is also a large variation between helmets with rotational protection; Figure 16.

Figure 16. Rotational velocity for helmets with rotational protection during oblique impact against the side of the helmet (rotation around the x-axis)



One of the helmets, Yakkay, which is available in a version in which it is possible to fit a cover in the form of a hat/cap, was tested both with and without the cover. A major difference was measured in the oblique tests between the Yakkay with and without the cover, which indicates that this cover provides good protection against rotational forces, similar to MIPS; Figure 17 and Figure 18. The difference is that the sliding shell in the case of the Yakkay is fitted on the outside of the shell of the helmet. It is probably not an intentional rotational protection, but shows that a surface-mounted layer can provide similar protection as a sliding layer fitted on the inside. There is a similar concept among motor cycle helmets, known as SuperSkin, which has been shown to reduce the rotational forces in oblique impact tests (PhillipsHelmets. 2015). Another example is the 6D helmet that consists of two layers of EPS linked with "dampers" that allow energy absorbing shear between the layers (6D Helmet. 2015). The Hövding did also obtain very good results in the rotational tests; Figure 17. When it is inflated, the exterior fabric can slide sideways in relation to the fabric on the inside against the head. Thus two shearing layers are created that considerably reduces the rotational acceleration. The above examples clearly demonstrate that there are several ways to design a helmet to absorb rotational forces.

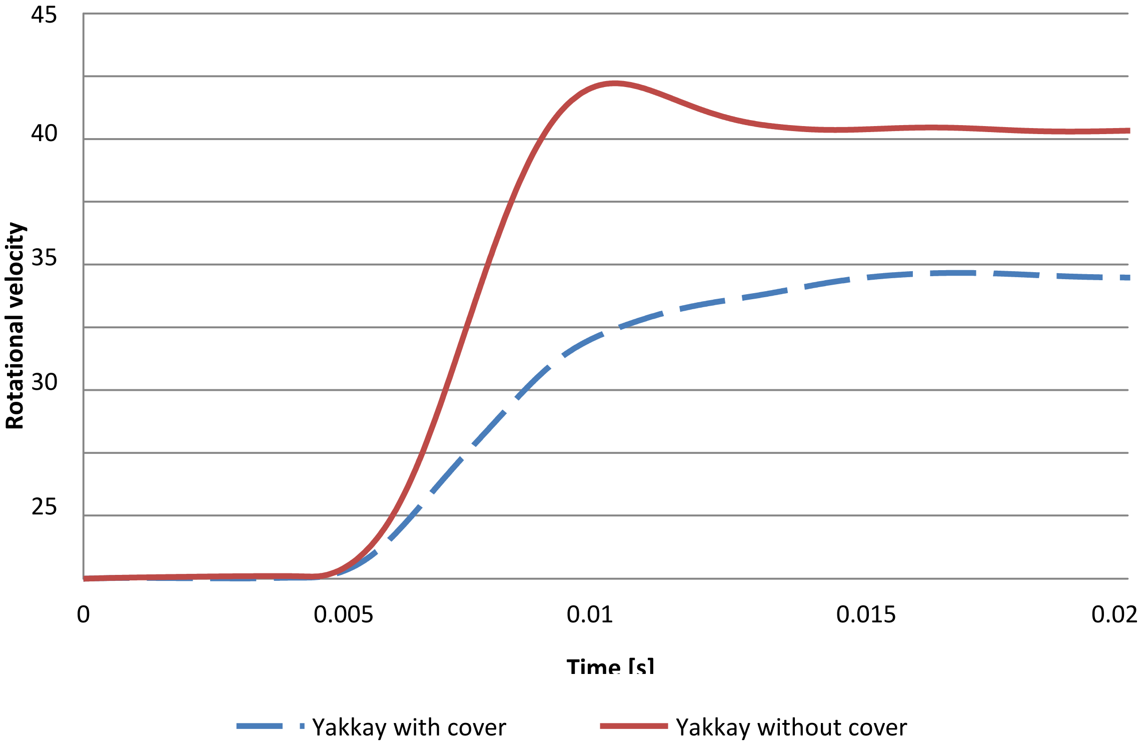


Figure 18. Rotational velocity during an oblique impact against the upper part of the helmet (Rotation in the y-axis)

One explanation for the variation in the helmet test results is also the difference in geometric design. A bicycle helmet design with many holes to achieve good ventilation and many edges in the outer shell is more likely to have a larger variation depending on the point of impact. When the Scott Stego MIPS is compared with the Bell Stoker MIPS, for example, the Bell helmet is round and smooth, whereas the Scott helmet has relatively marked design edges. The skate helmets are smoother but often have a harder outer shell and therefore generally obtain higher values. In addition, the variation may be caused by the fact that the helmet was not fitted equally firm on the crash dummy head. It was hard to check this. The helmets were fitted on the head with the intention that the neck adjustment system should be adjusted as similarly as possible using the same procedure as in the certification tests. The variation of the results reflects the variation in energy absorption, but also the fact that several helmet manufacturers do not develop the helmets for oblique impacts.

All the helmets included in the test comply with the legal requirements for a cycle helmet. However, the legal requirements do notcover the helmet's potential to reduce rotational forces. The results from Folksam's tests clearly indicate that a bicyclist using a helmet that meets the current legal requirements of 250 g can still get a concussion in case of an accident. Concussion or what is known as Mild Traumatic Brain Injury (MTBI) with or without loss of consciousness occurs in many activities, often as a result of the brain being subjected to rotational forces in the event of either direct or indirect forces against the head. Concussion can result in long-term or permanent symptoms such as memory disorders, headaches and other neurological symptoms. Eight per cent of the cases reported to Folksam in which a person suffers a head injury in connection with an accident lead to long-term symptoms with medical impairment (Malm et al. 2008). Rotation of the head may also lead to to more serious injuries such as diffuse axonal injury (DAI). To evaluate this risk a data simulation model was used.

In spite of the relatively high limit of 250 g in the legal requirements, studies indicate that current helmets have a good protective effect with a 60% reduction of head injury risk (Rizzi et al 2013). But the protective effect could be considerably higher if oblique impacts similar to those conducted in this study would be included. For a number of years the introduction of oblique impacts into the bicycle helmet standard (CEN/TC158-WG11, 2014) similar to the one used in the present study has been discussed. However, changing legal requirements is a long process and cannot be expected to be implemented within the next coming years. Therefore consumer test like this are important to increase consumer awareness when choosing cycle helmets and to influence helmet designers.

Thanks

Thanks are due to Mikael Videby and Karl-Gustaf Andersson, SP in Borås, for conducting the tests and to Peter Halldin, Department of Neuronics. School of Technology and Health, Royal Institute of Technology (KTH), for performing the data simulations.

Conflict of interests

Peter Halldin is also actively involved in MIPS AB and is one of the founders of the company behind the MIPS helmet. During the simulation the researcher did not know which helmets had been tested.

References

6DHelmet. *ODS™ (Omni-Directional Suspension™)* [Online]. Available from:
http://www.6dhelmets.com/#!ods/c10b6 [Downloaded 10/05/2015]

Asiminei A. Van der Perre G. Verpoest I and Goffin J (2009). A transient finite element study reveals the importance of the bicycle helmet material properties on head protection during an impact. Included in: The International Research Council on Biomechanics of Injury (IRCOBI) Conference. 2009 York. UK. 357–360.

Bjornstig U. Ostrom M. Eriksson A and Sonntag-Ostrom E (1992). Head and face injuries in bicyclists with special reference to possible effects of helmet use. *Journal of Trauma.* 33(6). pp. 887-893.

CEN/TC158-WG11 (2014). CEN/TC 158 - WG11 Rotational test methods.

Fahlstedt M (2015). *Numerical accident reconstructions - a biomechanical tool to understand and prevent head injuries.* Doctoral Thesis. Royal Institute of Technology (KTH).

Gennarelli T. Thibault L. Tomei G. Wiser R. Graham DI and Adams J (1987). Directional dependence of axonal brain injury due to centroidal and non-centroidal acceleration. Included in: Proceedings of the 31st Stapp Car Crash Conference. Society of Automotive Engineers. 1987 Warrendale. PA.

Hansen K. Dau N. Feist F. Deck C. Willinger R. Madey SM and Bottlang M (2013). Angular impact mitigation system for bicycle helmets to reduce head acceleration and risk of traumatic brain injury. *Accident Analysis and Prevention.* 59. pp. 109-117.

Holbourn AHS (1943). Mechanics of head injury. *Lancet* 2. pp. 438-441.

Kleiven S (2003). Influence of impact direction on the human head in prediction of subdural hematoma. *Journal of Neurotrauma.* 20(4). pp. 365-379.

Kleiven S (2006a). Biomechanics as a forensic science tool - reconstruction of a traumatic head injury using the finite element method. *Scand J Forens Sci..* (2). pp. 73-78.

Kleiven S (2006b). Evaluation of head injury criteria using a finite element model validated against experiments on localized brain motion. intracerebral acceleration. and intracranial pressure. *Internal Journal of Crashworthiness.* 11(1). pp. 65-79

Kleiven S (2007). Predictors for traumatic brain injuries evaluated through accident reconstructions. *Stapp Car Crash J.* 51. pp. 81-114.

Kleiven S and Hardy WN (2002). Correlation of an FE model of the human head with local brain motion: Consequences for injury prediction. *46th Stapp Car Crash Journal: 123-144.*

Löwenhielm P (1975). Mathematical simulations of gliding contusions. *J. Biomech..* Vol. 8. Issue 6. pp. 351-356 doi:10.1016/0021-9290(75)90069-X.

Malm S. Krafft M. Kullgren A. Ydenius A and Tingvall C (2008). Risk of permanent medical impairment (RPMI) in road traffic accidents. *Annu Proc Assoc Adv Automot Med.* 52. pp. 93-100.

Margulies SS and Thibault LE (1992). A proposed tolerance criterion for diffuse axonal injury in man. *Journal of Biomechanics.* 25(8). pp. 917-923.

Mertz HJ. Prasad P and Irwin AL (1997). Injury risk curves for children and adults in frontal and rear collisions. Included in: Proceedings of the 41th Stapp Car Crash Conference. 1997 Lake Buena Vista. Florida. US. 13–30.

Mills NJ and Gilchrist A (2006). Bicycle helmet design. *Journal of Materials.* Proceedings of the Institution of Mechanical Engineers. Part L(Design and Applications 220). pp. 167-180.

Newman JA. Beusenberg MC. Shewchenko N. Withnall C and Fournier E (2005). Verification of biomechanical methods employed in a comprehensive study of mild traumatic brain injury and the effectiveness of American football helmets. *Journal of Biomechanics.* 25(8). pp. 1469-81.

Newman JA. Shewchenko N and Welbourne E (2000). A proposed new biomechanical head injury assessment function - the maximum power index. *Stapp Car Crash J.* 44. pp. 215-47.

Patton DA (2014). *The biomechanical determinants of sports-related concussion: Finite element simulations of unhelmeted head impacts to evaluate kinematic and tissue level predictors of injury and investigate the design implications for soft-shell headgear.* PhD Thesis. University of New South Wales.

PhillipsHelmets. *Phillips head protection system* [Online]. Available from: http://www.phillipshelmets.com [Downloaded 10/05/2015]

Rizzi M. Stigson H and Krafft M (2013). Cyclist injuries leading to permanent medical impairment in Sweden and the effect of bicycle helmets. Included in: Int. IRCOBI Conf. on the Biomechanics of Injury. 2013 Gothenburg. Sweden.

SS-EN1078 Helmets for pedal cyclists and for users of skateboards and roller skates. (1997).

Stigson H. Hasselwander M. Krafft M. Kullgren A. Rizzi M and Ydenius A (2012). In Swedish: Folksams cykelhjälmtest juni 2012. [Folksam's cycle helmet test June 2012]. Included in: Folksam Research.

Stigson H. Krafft M. Rizzi M. Kullgren A. Ydenius A and Lindmark K (2013). Folksam's cycle helmet test May 2013. Included in: Folksam Research.

Thompson DC. Rivara FP and Thompson R (2009). Helmets for preventing head and facial injuries in bicyclists (Review). *Cochrane Database of Systematic Reviews 1999.* (Issue 4. Art. No. CD001855. DOI: 10. 1002/14651858. CD001855).

Willinger R. Deck C. Halldin P and Otte D. (18-19 November 2014). Towards advanced bicycle helmet test methods. Included in: International Cycling Safety Conference 2014. 18-19 November 2014 Gothenburg. Sweden.

Zhang L. Yang KH and King AI (2004). A proposed injury threshold for mild traumatic brain injury. *Journal of Biomechanical Engineering.* 126(2). pp. 226-36.

Appendix A – Graphs of test values from the three rotation tests

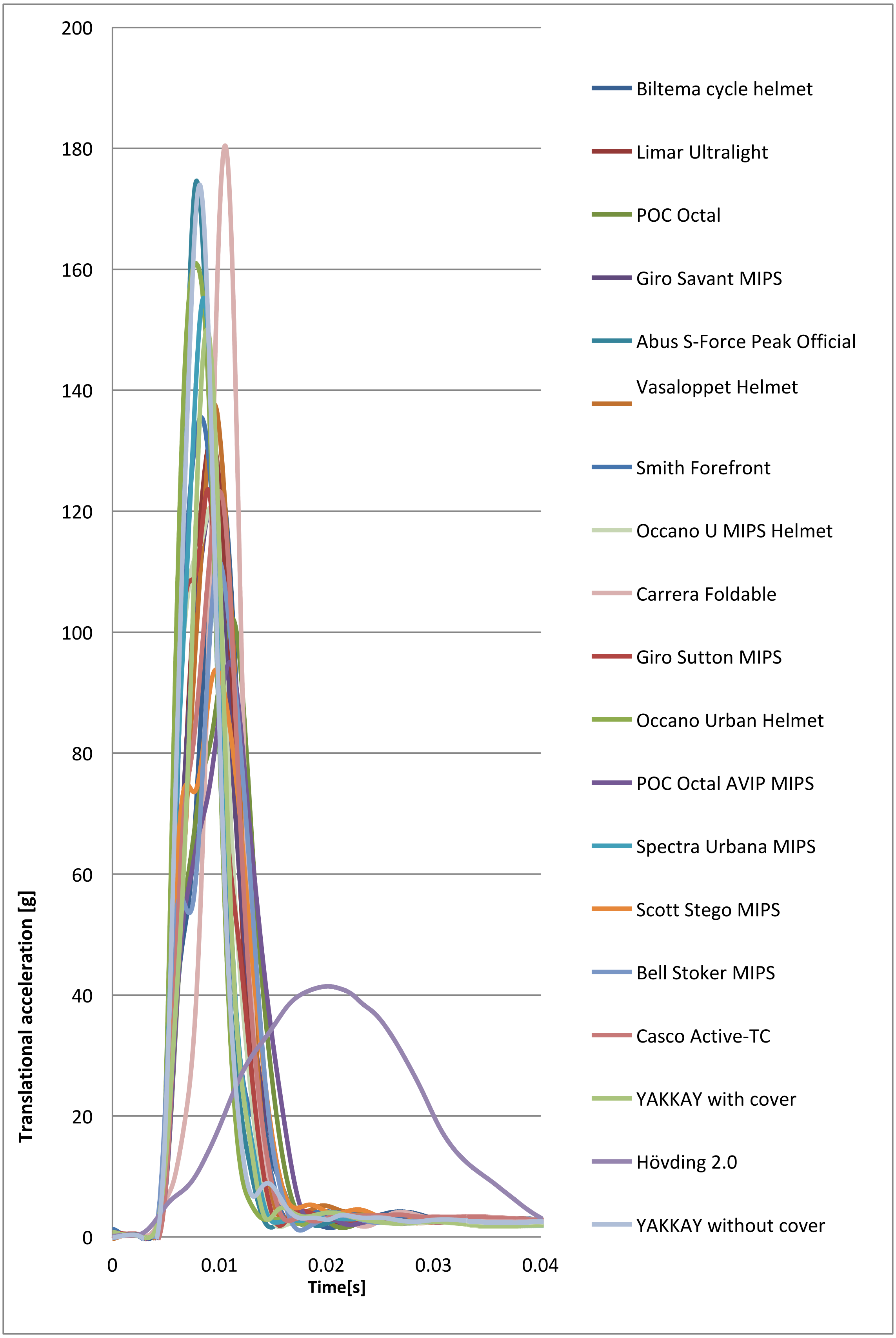


Figure A. Translational acceleration during oblique impact against the side of the helmet (rotation in the x-axis)

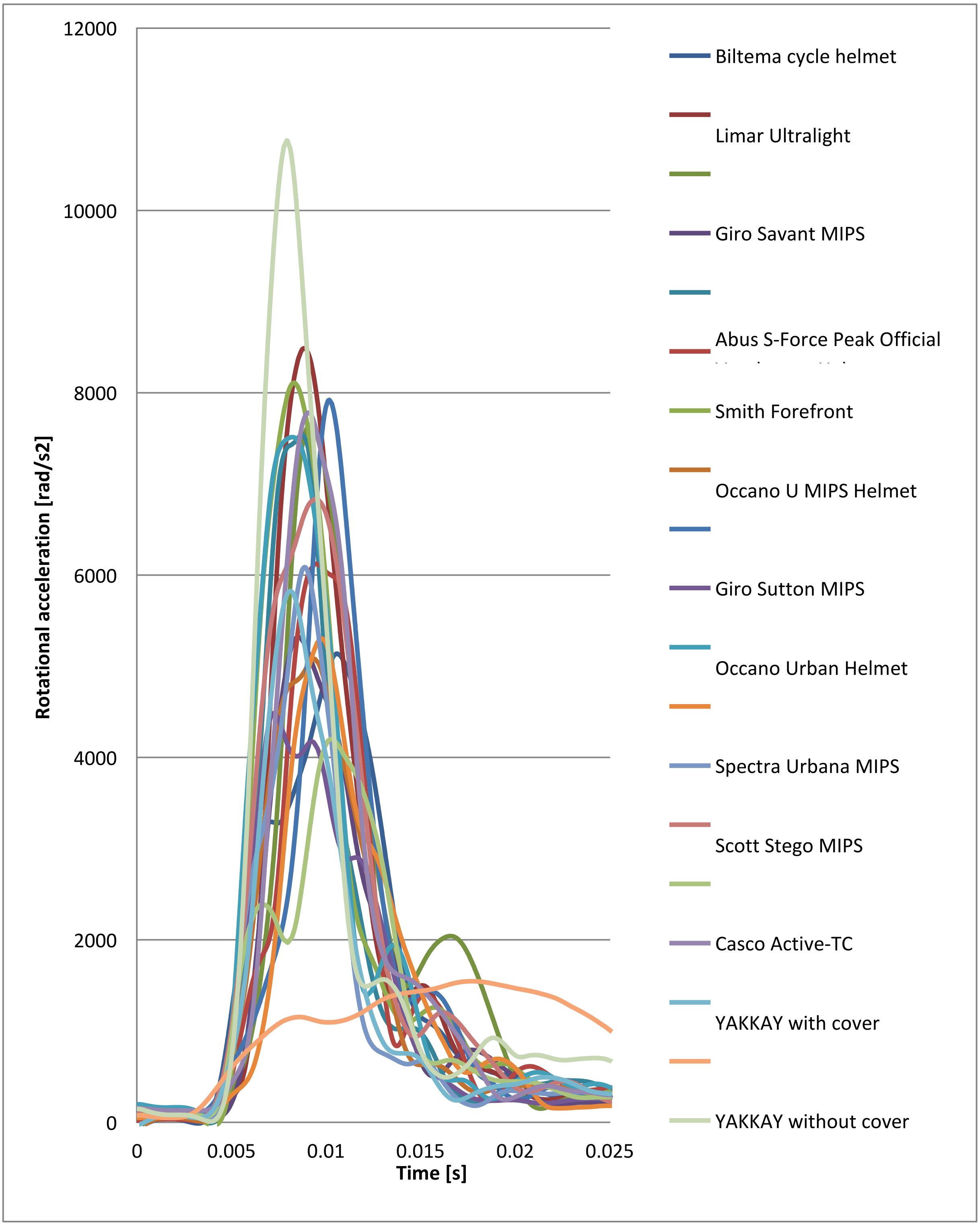


Figure B. Rotational acceleration during oblique impact against the side of the helmet (rotation in the x-axis)

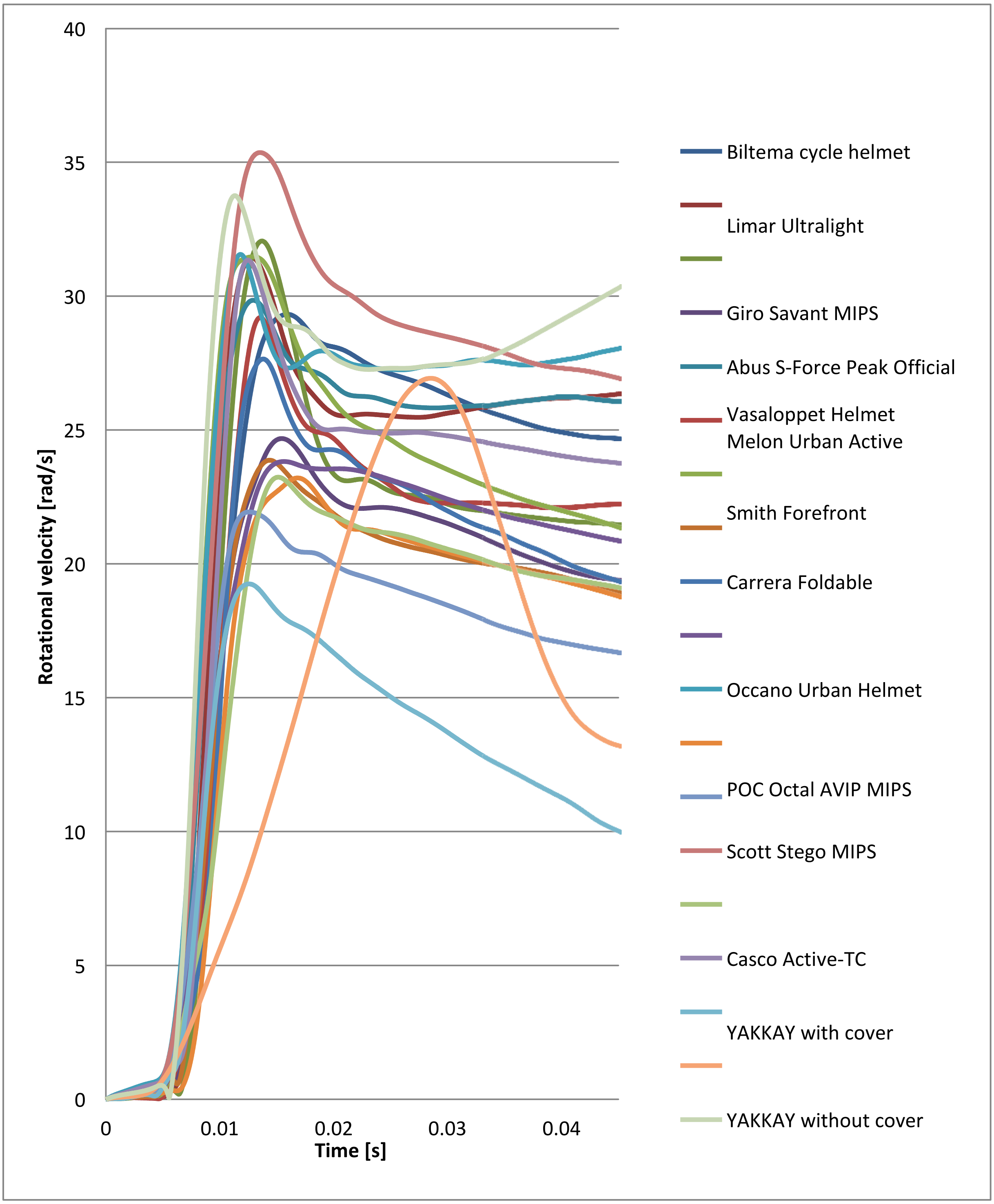


Figure C. Rotational velocity during oblique impact against the side of the helmet (rotation in the x-axis)

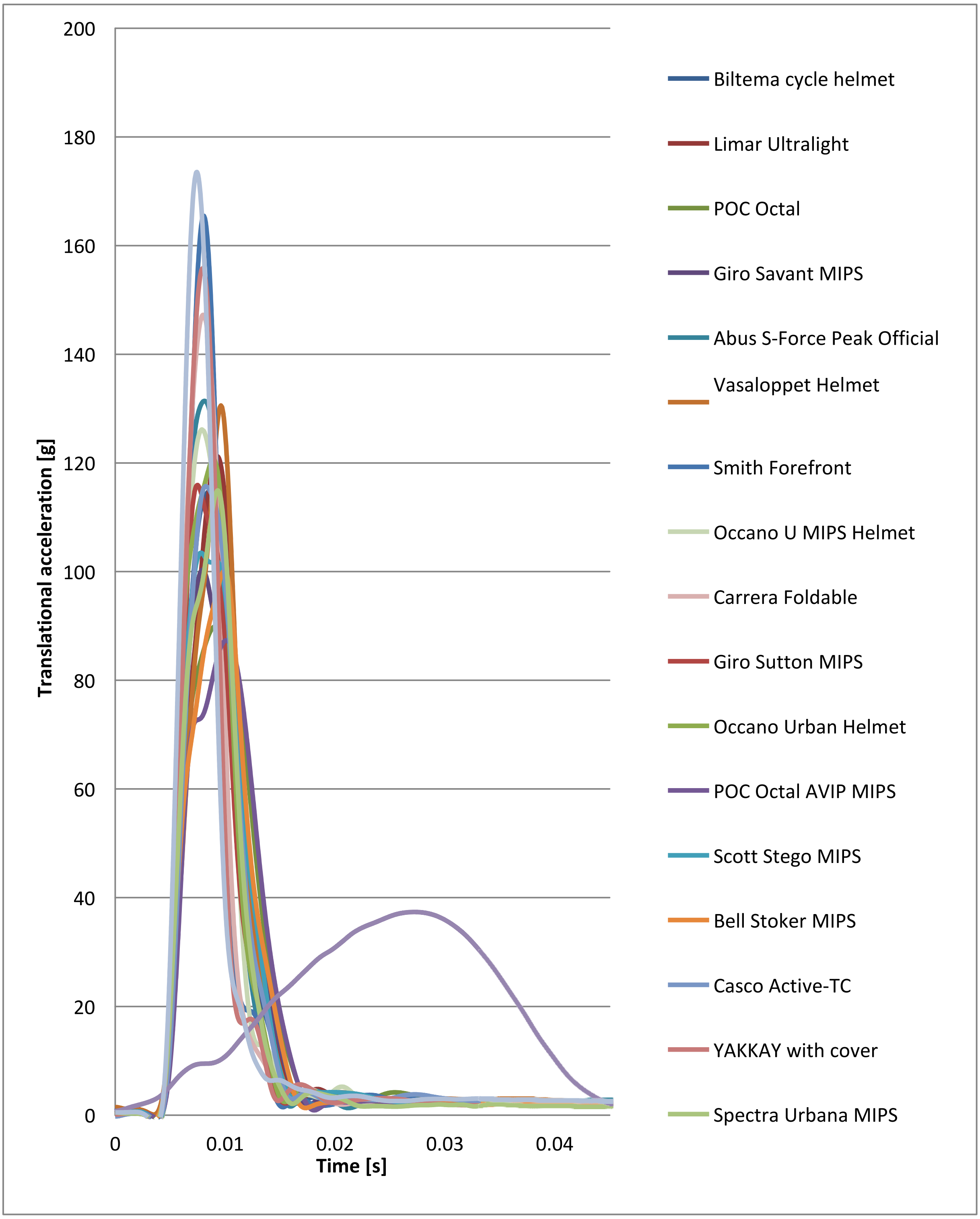


Figure D. Translational acceleration during oblique impact against the upper part of the helmet (rotation in the y-axis)

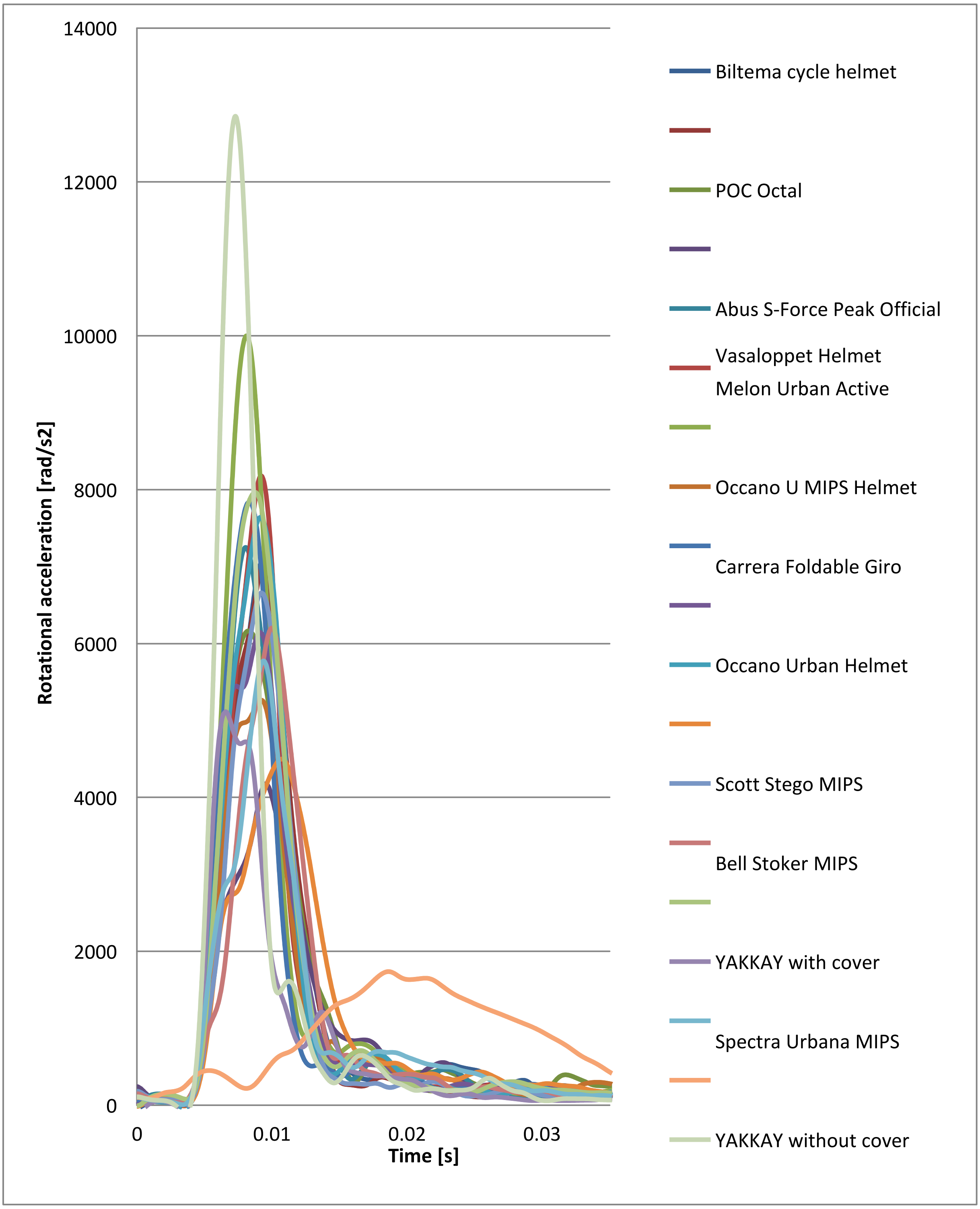


Figure E. Rotational acceleration during oblique impact against the upper part of the helmet (rotation in the y-axis)

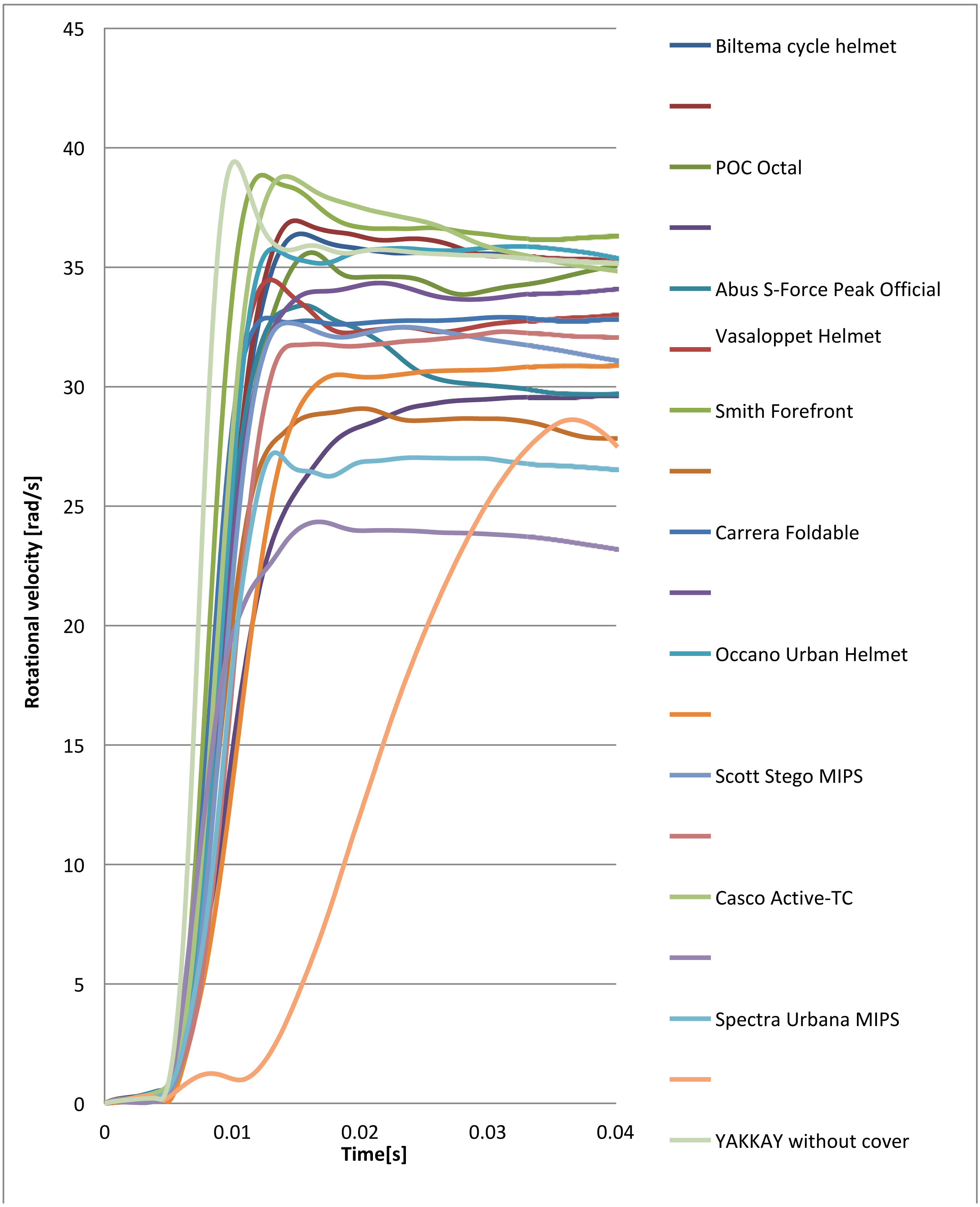


Figure F. Rotational velocity during oblique impact against the upper part of the helmet (rotation in the y-axis)

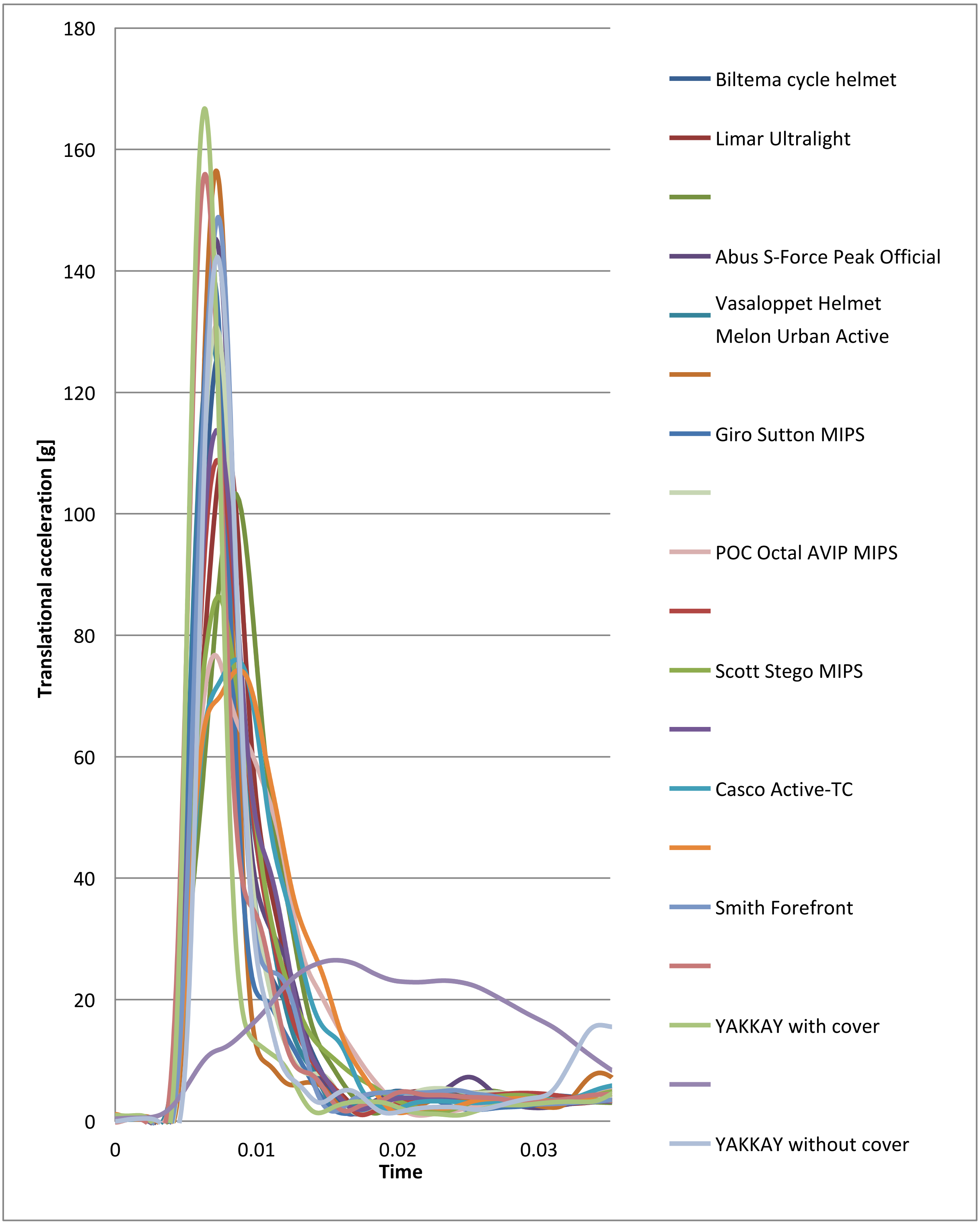


Figure G. Translational acceleration during an oblique impact against the rear part of the side of the helmet (rotation in the z-axis)

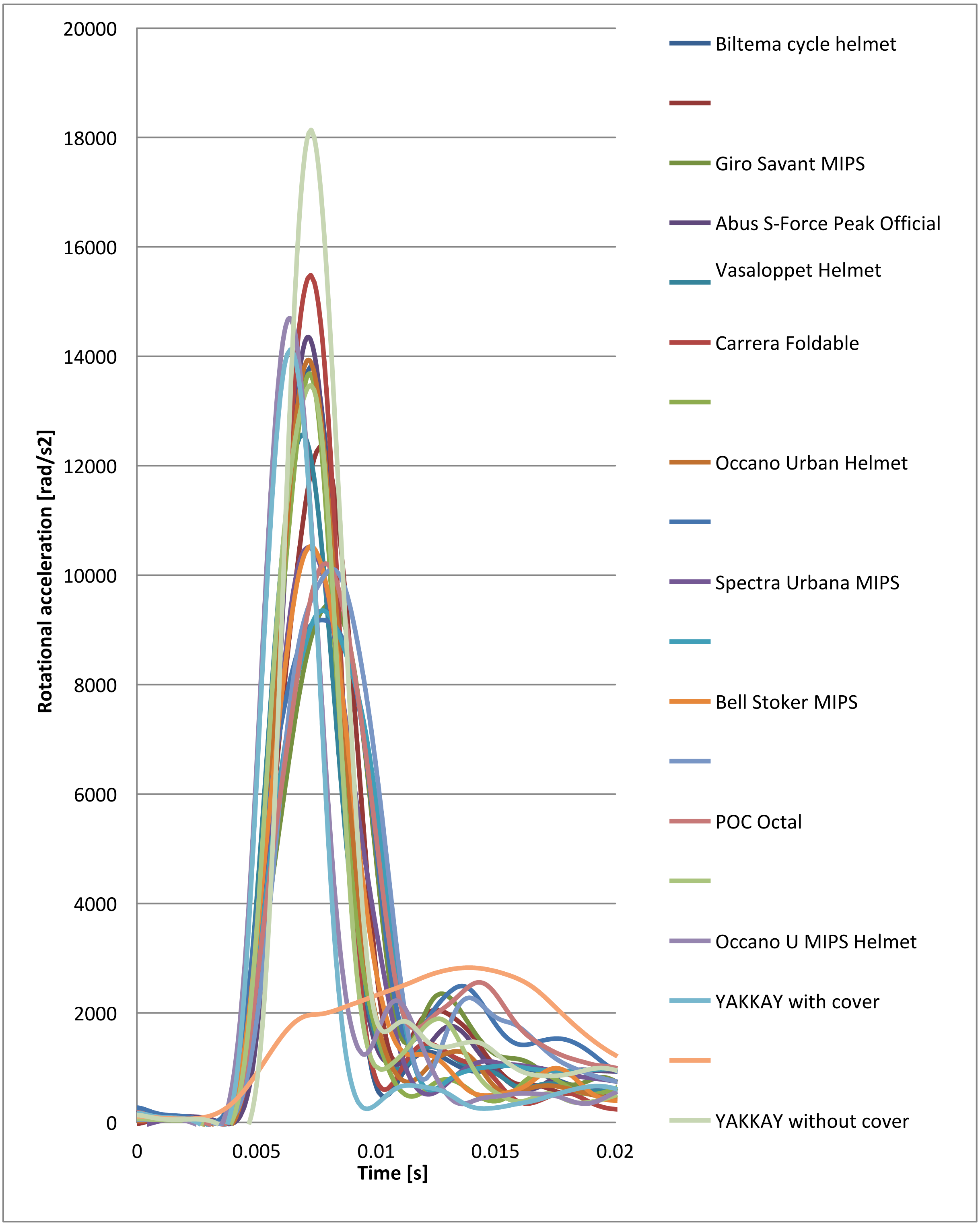


Figure H. Rotational acceleration during an oblique impact against the rear part of the side of the helmet (rotation in the z-axis)

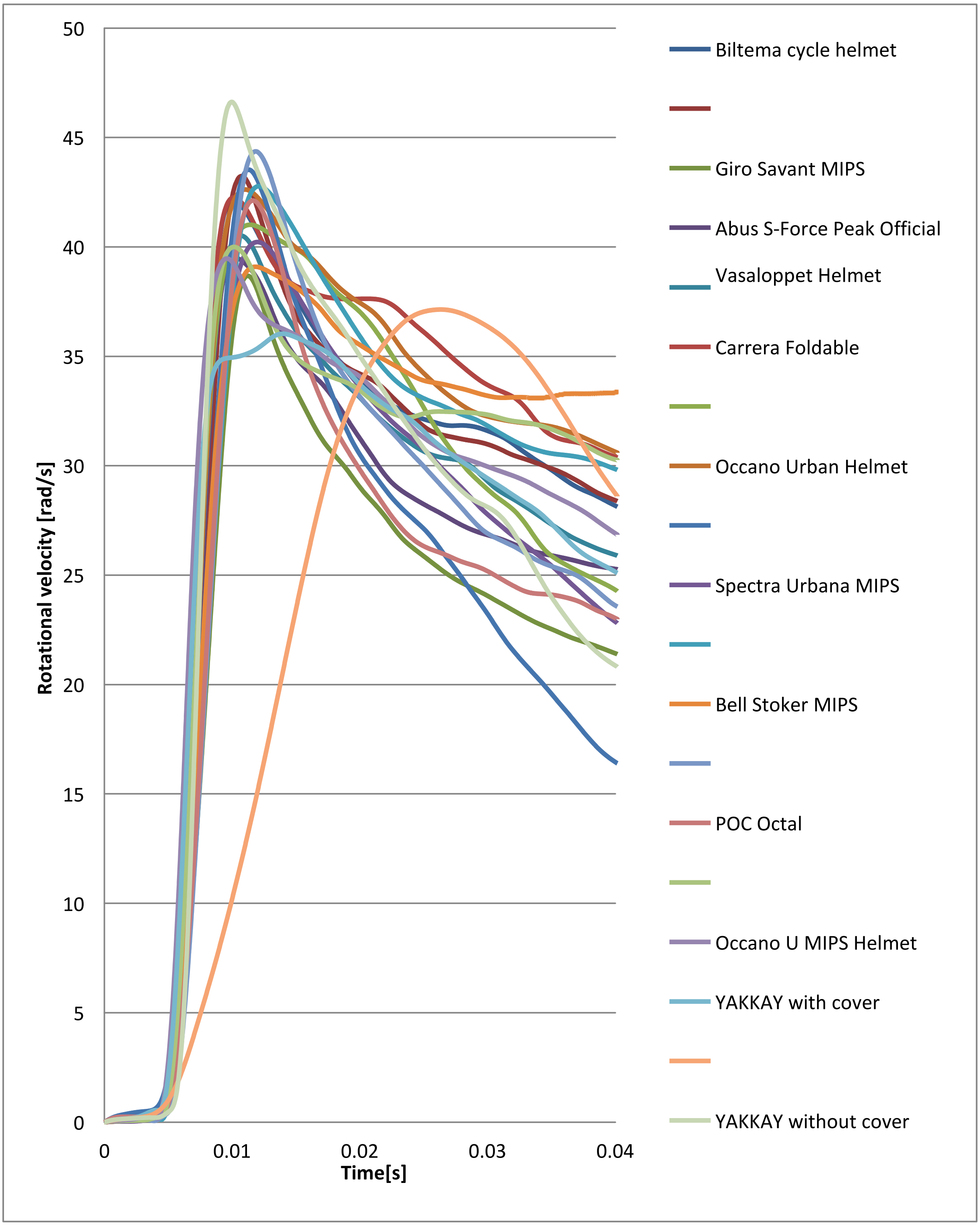


Figure I. Rotational velocity during an oblique impact against the rear part of the side of the helmet (rotation in the z-axis)

Appendix B – Hövding

Hövding 2.0 is a bicycle helmet in the form of a collar, which contains an airbag protecting the head in case of an accident. The movements of the bicyclist are continuously recorded by sensors and if an abnormal pattern of movement is detected the airbag inflates. Inflation takes a tenth of a second. The pressure in the airbag is maintained for several seconds. The Hövding's capacity to detect an accident or critical situation was not included in the test. However, during the development of the product and during CE marking the company itself performed crash tests at SP and VTI to ensure that it is activated. During these procedures they used both crash test dummies and stuntmen.

A limitation with the Hövding is that it does not provide protection when the head is struck directly by an object when cycling, i.e. without falling off the bicycle. This can occur if the head strikes a branch or post during cycling.

Impact of a neck on the test head

Since a neck is expected to provide the necessary support for the Hövding in the rotation tests, comparative tests were conducted both with and without a neck on the test head. A Hövding 2.0 with a neck only had a slightly higher rotational velocity than one without; Figure A and Table A. The test results for the Hövding 2.0 without a neck are reported in the study. The reason for this is that for a conventional helmet it has a significant effect on the test results if it is tested with a neck, see Figure A. The accident scenario and also the test scenario are very short (10-20 ms) for a conventional helmet and previous studies have shown that the neck is only rotated 10 degrees during this procedure. It is therefore probably a completely realistic scenario for the conventional helmets not to use a neck. Several researchers have highlighted that this should be investigated further (Fahlsted, 2015) and that it is particularly important to investigate the impact the neck has on longer impact durations, such as for the Hövding 2.0 head protector.

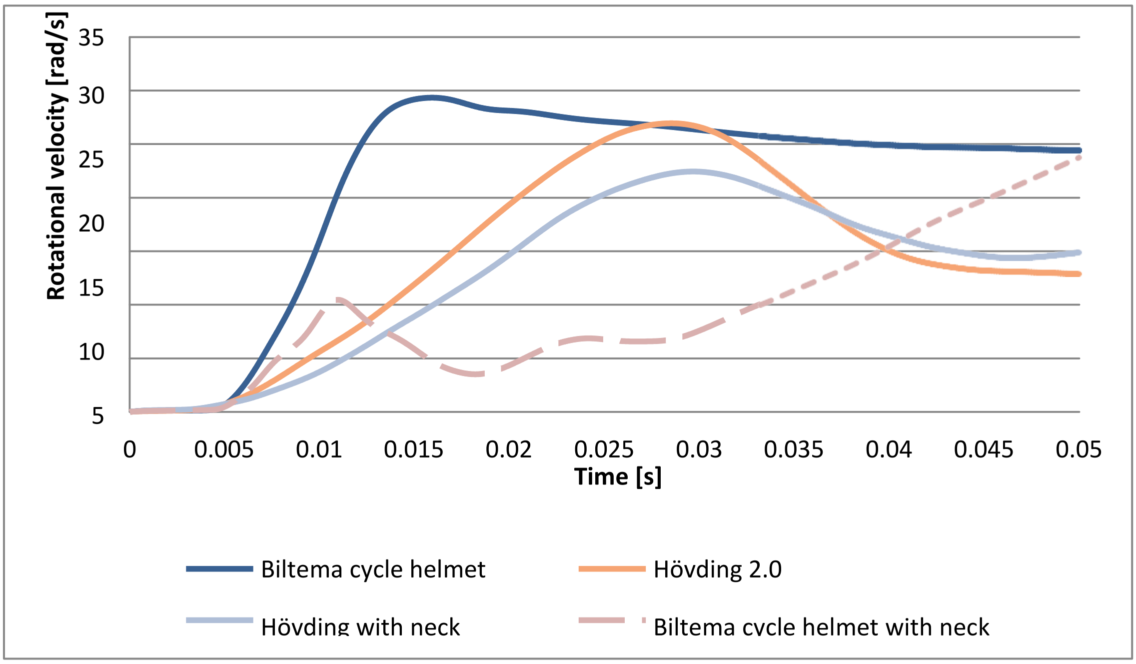


Figure A. Rotational velocity with and without neck for a conventional helmet and the Hövding 2.0

Table A Strain values from simulation with and without neck

	Strain (%)		
Simulation	Rotation around x-axis	Rotation around y-axis	Rotation around z-axis
Hövding	6.2	7	19
Hövding with neck	6.8	10	18
Biltema	19.0	25	34
Biltema with neck	5.6	16	36

SP-method 4439

Inflatable head protective devices with electronic triggering system for pedal cyclists

Klas-Gustaf Andersson
Lars Andersson
Christian Larsson

Foreword

This document has been prepared by SP Technical Research Institute of Sweden. This document supports the essential requirements of EU Directive 89/686/EEC.

Introduction

The protection given by a head protector depends on the circumstances of the accident and wearing a head protector cannot always prevent death or long term disability.

A proportion of the energy of an impact is absorbed by the inflated head protector, thereby reducing the force of the blow sustained by the head. When the head protector has inflated it shall be replaced if it is of a non-rechargeable type.

To achieve the performance of which it is capable, and to ensure stability on the head, it is of great importance that the head protector is of a shape that fits the user’s head and neck.

When an inflatable head protector is used in normal bicycling there is no protection against a direct hit to the head. Also the head protector offers limited protection against pointed objects.

1 Scope

This test method is applicable to performance requirements and tests for inflatable head protectors for pedal cyclists. The standard for helmets for bicyclists, EN 1078 has been considered during the development of this test method but requirements and test methods have been developed that are not covered by EN 1078 since inflatable head protectors are outside the scope of that standard. Some requirements from EN 1078 are not applicable to an inflatable head protector, i.e. retention system properties and field of vision because in normal use the protector is not inflated. The head protector is not intended for use during mountain biking or competition. The head protector does not offer protection in direct hit accidents and offers limited protection when the head protector has only partially reached inflated status prior to head impact.

Requirements and the corresponding method of test, where appropriate, are given for the following:

- Construction
- Sizing, ergonomics and innocuousness
- Minimum protected area
- Duration of inflated status
- Trigger system function
- Shock absorbing capacities
- Wear resistance
- Blocked deployment
- Labelling and information

2 References

EN 340, Protective clothing – General requirements

EN 960, Headforms for use in the testing of protective helmets

EN 1078, Helmets for bicyclists and for users of skateboards and roller skates

EN 13087-1, Protective helmets – Test methods – Part 1 – Conditions and conditioning

EN 13087-2, Protective helmets – Test methods – Part 2 - Shock absorption

prEN 1621-4, Motorcyclists' protective clothing against mechanical impact – Part 4: Motorcyclists' inflatable protectors – Requirements and test methods

ISO 6330, Textiles - Domestic washing and drying procedures for textile testing

46 CFR, Part 572 - Anthropomorphic Test Devices, Subpart B – 50th Percentile Male

EN 13595-2, Protective clothing for professional motorcycle riders - Jackets, trousers and one-piece or divided suits - Part 2: Test method for determination of impact abrasion resistance

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1 General

3.1.1 Acceleration of a body

a (self-explanatory).

NOTE: Acceleration is measured in metres per second squared, in units of g.

3.1.2 Acceleration of a body due to gravity

g (self-explanatory, g = 9,806 m/s2).

3.1.3 Maximum value of acceleration

a_{max} - maximum acceleration encountered during impact, in units of g. The maximum acceleration is calculated as the maximum value of the resultant of the accelerations of the three axes recorded by a tri-axial accelerometer.

3.1.4 Natural frequency

Frequency at which a system will tend to oscillate when displaced from its static equilibrium position.

3.1.5 Drop height

Vertical distance between the lowest point (impact point) of the elevated headform and the impact surface.

3.1.6 Area to be protected

Specific area of the protective equipment that is intended to provide protection and this area is subject to specific testing.

3.1.7 Permanent marking and warning

Information that remains legible and cannot be removed in its entirety under normal use conditions. See Clause 6.

3.1.8 Securely attached label and tag

Label or tag affixed at the time of manufacture, and which is normally removed at the time of head protector use.

3.1.9 Normal bicycling

Normal bicycling refers to the kind of bicycling that is performed in an urban environment or on the road (continuous pedaling, irregular pedaling, turns, turns to look round, etc.), to travel from one point to another, but also movements made associated with bicycling, such as bending down to unlock the bicycle. Other challenging movements on the bicycle which are considered as normal include:

- performing repeated "slalom turns" while riding,
- standing up and going as fast as you can and then jam on the brakes,
- to jam on the brakes sitting down at high speed,
- lifting the front wheel while riding, i.e. jumps with the bike,
- bending the upper body side to side while riding,
- to rotate the upper body side to side quickly while riding,
- to bend down and check the bicycle chain while riding,
- to ride up and down curbs,

3.2 Inflatable head protector

3.2.1 Head protector

Device intended to reduce the risk of head injury to pedal cyclists and including:
a) the outer covering and shock-attenuating system,
b) all associated software

3.2.2 Head protector type

Category of head protectors that do not differ in such essential respects as the materials, dimensions, construction of the head protectors, the inflatable padding or the software controlling the trigger function.

3.2.3 Activation time

Time from accident detection to inflated status.

3.2.4 Power-up-time

Time period from triggering system start to activation of the accident detection.

3.2.5 Triggering system

System which is triggering the inflatable head protector after correctly identifying scenarios where deployment of the inflatable head protector shall be beneficial.

3.2.7 Direct hit

Accident where the head takes the first impact.

3.2.8 Inflated status

Status where the head protector is inflated to its working pressure.

3.2.9 Working pressure

Pressure in the inflatable head protector as specified by the manufacturer. This equals the pressure needed by the head protector to fulfil the shock absorption test.

3.2.10 Shoulder and head dummy

Shoulder dummy, see figure 2, combined with an EN 960 headform of a size corresponding to the head protector’s size marking.

3.2.11 Circuit breaker

Device activating the head protector’s triggering system, such as a push button, zipper etc.

3.2.12 Function indicator

Device showing that the head protector’s triggering system is activated.

4 Requirements

4.1 Materials

4.1.1 Innocuousness

Protective clothing shall not adversely affect the health or hygiene of the user. Protective clothing shall be made of materials such as textiles, leather, rubbers, plastics that have been shown to be chemically suitable. The materials shall not in the foreseeable conditions of normal use release or degrade to release substances generally known to be toxic, carcinogenic, mutagenic, allergenic, toxic to reproduction or otherwise harmful. Information claiming that the product is innocuous shall be checked.

NOTE 1 - Information on the classification and identification of harmful substances can be found e.g. in [7, 8] of the Bibliography in EN 340.

NOTE 2 - Guidance on how to consider acceptability of materials in protective clothing is given in informative annex B (flow chart) of EN 340.

NOTE 3 - Materials should be selected to minimise the environmental impact to the production and disposal of protective clothing.

NOTE 4 - The following list of documents is given for information and as examples of documents to be examined:

a) Information supplied by the manufacturer could include a declaration confirming that the product does not contain any substances at levels that are known or suspected to adversely effect user hygiene or health,
b) Materials specifications,
c) Safety data sheets relating to the materials,
d) Information relating to the suitability of the materials for use with food, in medical devices, or other relevant applications.
e) Information relating to toxicological, allergenic, carcinogenic, toxic to reproduction or mutagenic investigations on the materials,
f) Information relating to ecotoxicological and other environmental investigations on the materials,

The examination should determine whether the claim that the materials are suitable for use in the protective clothing or protective equipment is justified. Particular attention has to be paid to the presence of plasticisers, unreacted components, heavy metals, impurities and the chemical identity of pigments and dyes.

Materials of protective clothing shall comply with the following requirements:
a) The chromium VI content in leather clothing shall comply with the requirements of EN 420.
b) All metallic materials which could come into prolonged contact with the skin (e.g. studs, fittings) shall have an emission of nickel of less than 0,5 µg/cm² per week. The method of test shall be according to EN 1811.
c) The pH value for protective clothing material shall be greater than 3,5 and less than 9,5. The test method for leather shall be according to EN ISO 4045 and for other materials according to EN 1413.
d) The colour fastness to perspiration of protective clothing material to ensure user hygiene (e.g. no skin staining) shall be determined in accordance with EN ISO 105-A02 and shall be at least grade 4 of the Grey scale for the colour change of the specimen. The test shall be conducted in accordance with EN ISO 105-E04.
e) Azo colorants which release carcinogenic amines listed in prEN 14362-1 shall not be detectable by the method in that standard.

4.1.2 Washing instructions

The manufacturer must give information regarding washing procedures of the protector (if applicable). If it can be expected that the washing process can affect the head protector’s properties then the head protector shall be conditioned in accordance with 5.3.5 prior to testing according to 5.9. Samples number 13-16 shall be used.

4.2 Construction

The head protector shall be so designed and shaped that parts of it (for example zippers, gas generators etc) are not likely to injure the user. It shall be designed so that during normal bicycling, it is unlikely to become dislocated. It shall also be designed so that the way to put it on and wear it is obvious/natural to the user. This shall also be indicated in the product’s marking and in the instructions for use.

Movements and positions during normal bicycling must be executable without considerable discomfort.
The requirements for construction can be verified in accordance with 5.2.

NOTE: Inflatable head protectors should:

- be easy to put on and take off;
- have low weight;
- be well fitting.

4.3 Area to be protected

When tested in accordance with 5.4, after inflation on a headform of appropriate size, the head protector shall cover at least the area defined by points BCDJLM as defined in 5.5.3.

4.4 Shock absorbing capacitiy

When tested in accordance with 5.5 the peak acceleration (a_{max}) shall not, for each impact, exceed 250 g.

4.5 Duration of inflated status

For the time declared by the manufacturer, the bag shall remain in inflated status. This time shall be not less than 2 seconds and not more than 10 seconds. This time shall be measured in accordance with 5.7

4.6 Temperature exposure evaluation

Certain gas generators, which contain pyrotechnic components, can generate hot gases when fired. These products shall be subjected to a temperature exposure evaluation in accordance with 5.8.

The average temperature recorded over the duration of the test shall not exceed 50 °C.

The product shall be examined to identify surfaces on or adjacent to the inflatable chamber, which contact the skin, where an excess amount of heat could be transmitted.

4.7 Evaluation of the function of the triggering system

4.7.1 Evaluation using a test dummy

When tested in accordance with 5.9, the inflatable head protector shall deploy and protect the test dummy’s head before impact, i.e. reach inflated status. During the test, contact between the head of the test dummy, within the area to be protected, and the impact surface, i.e. car dummy or ground, is not permitted.

4.7.2 Evaluation using a test person

When tested in accordance with 5.9, the time between accident detection and head impact shall not exceed the time needed to reach inflated status.

4.7.3 Alternative evaluation

If head impact occurs before the head protector has reached inflated status, the manufacturer can choose to have the shock absorption test performed at the actual pressure at head impact. This pressure can be taken from the time/pressure graph determined in the test according to 5.6. If the head protector passes the shock absorption test at this pressure, then the requirements in clauses 4.7.1 and 4.7.2 shall be considered to be fulfilled.

4.8 Drop test

When dropped onto a drop test plate from 2 m, the inactivated head protector shall not deploy. The head protector shall function normally after the test or indicate that it is not functioning. Test according to 5.10.

4.9 Acoustic test

When deployed, the noise level measured at the test dummy’s ear shall not exceed 135 dB. Test according to 5.11.

4.10 Function test following conditioning

After exposure to low and high temperature and ageing, the head protector shall still function normally. Test according to 5.12.

4.11 Resistance to false accident detection during normal bicycling

When tested according to 5.13, the head protector shall not indicate accident detection.

4.12 Wear resistance

When tested according to 5.15, the airbag fabric shall withstand perforation for at least 0.5 s.

4.13 Function indicator

An indicator showing that the head protector is activated must be present. This indicator must be clearly visible and audible to the user. If the head protector’s function is dependent on battery power, there must be a warning signal before the function ceases. After the warning signal has indicated, the head protector’s function shall remain for at least 1 hour. Test according to 5.14.

NOTE: It is recommended that the Power-up-time is less than 10 s.

4.14 Durability

After being tested the head protector shall not show damage that could cause an additional injury to the wearer’s head (sharp edges, points etc.). This can be verified in accordance with 5.2.

4.15 Blocked deployment

When tested in accordance with 5.16, the maximum force shall not exceed 900 N.

4.16 Pressure equipment

The gas generator shall fulfill the requirements for Pressure Equipment in accordance with directive 97/23/EC. This shall be included in the manufacturer’s technical documentation.

4.17 EMC

The head protector and its components shall fulfil the requirements in accordance with the electromagnetic compability directive 2004/108/EC, emission and immunity. This shall be included in the manufacturer’s technical documentation.

4.18 Low voltage

The head protector and its components shall fulfil the requirements in accordance with the low voltage directive 2006/95/EC. This shall be included in the manufacturer’s technical documentation.

5 Testing

5.1 Sampling

For the tests, the following set of test samples is needed:

Samples 1-8 shall be head protectors without gas generator but with means of inflating the head protector manually and the possibility to measure the pressure;
Samples 9-12 shall be head protectors with gas generator and manual triggering and the possibility to measure the pressure;
Samples 13-16 shall be new and complete head protectors as offered for sale*;
Samples 17 and 18 shall be head protectors with inert inflator but with means of indicating inflating.
Samples 19-22 shall be a head protector with gas generator and manual triggering;

For the new and complete head protectors as offered for sale, the duration between the date of manufacture and the date of testing shall be not less than 6 days.

* If test persons are used instead of test dummy then the head protectors for these tests shall have the same specifications as samples 17-18.

Table 1 – Sequence of tests and number of tests per sample

Performance test	Sequence of tests	Sample number/conditioning			
5.5 Determination of shock absorbing capacity	1st	1 and 2 [1] (ambient)	3 and 4 [1] (ambient)	5 and 6 [1] (ambient)	7 and 8 [1] (reserves) (ambient)
5.4 Determination of the area to be protected, 5.6 Determination of activation time, 5.7 Duration of inflated status, 5.8 Temperature exposure evaluation (applicable only for hot gas generators), 5.12 Function test following conditioning	2nd	9 (+50)	10 (-20)	11 (aged)	12 (ambient)
5.10 Drop test	3rd	13 [2] (ambient)			
5.14 Function indicator	4th	14 (ambient)			
5.9 Evaluation of the function of the mechanism of activation	5th	13 (ambient)	14 (ambient)	15 and 16 (ambient)	17 and 18 (ambient)
5.11 Acoustic test	6th	19 (ambient)			
5.13 Accidental inflation during bicycling	7th	17 (ambient)	18 (ambient)		
5.15 Wear resistance test	8th	3 test specimens			
5.16 Blocked deployment test	9th	20	21	22	

[1] The manufacturer may choose to perform the two impacts on the same sample.

[2] If no. 13 is destroyed during the drop test, a reserve sample provided by the manufacturer shall be used for the test according to 5.9.

5.2 Visual and tactile inspection and wearer trial

5.2.1 Inspection and determination of mass

Inspect the head protector to ascertain whether it is suitable for its intended purpose and fulfils the general requirements in 4.2 (Construction). If no test method is specified in this document the compliance with the requirements have to be checked by visual and/or tactile examination.

Determine and record the mass of the head protector, stating the size of the head protector.

5.2.2 Testing of ergonomics and comfort

The head protector shall be placed on a test person representative for the actual head protector size and according to the manufacturer's instructions. The person shall check that, during normal use, i.e. bicycling according to the manufacturer's instructions, normal positions can be reached and movements can be done without any appreciable discomfort.

5.3 Conditioning

5.3.1 Testing atmosphere (room conditioning)

Unless otherwise stated, testing in accordance with this document shall be performed in an atmosphere with a temperature of (22 ± 5)° C and a relative humidity of (55 ± 30)%. Samples to be tested in a room conditioned state shall be exposed to this atmosphere for not less than 4 h.

5.3.2 High temperature conditioning

The sample shall be exposed to a temperature of (50 ± 2)° C for not less than 4 h.

5.3.3 Low temperature conditioning

The sample shall be exposed to a temperature of (-20 ± 2)° C for not less than 4 h.

5.3.4 Artificial ageing

The outer surfaces of the head protector shall be exposed successively to:

- ultraviolet radiation by a 125 W xenon-filled quartz lamp for 48 h at a range of 250 mm.
- spraying with water at a rate of 1 l/min for a period of time between 4 h and 24 h. Tap water at a temperature not greater than 27° C shall be used. As an alternative, the following method can be used:

  Place the head protector under a drip box specified for IPX1, see EN 60529 Figure 3a, but with the protector angled as specified for IPX2, see EN 60529 Figure 3B. Subject the head protector to a water flow rate of (1 +0.5/0) mm/min for 110 minutes. Following this take the head protector and place it under an oscillating tube specified for IPX1, see EN 60529 Figure 4, and subject the head protector to a water flow rate of 0.56[1] l/min ±5 % for 10 minutes.

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[1] The stated flow rate assumes that a tube radius of 200 mm can be used. Should a larger tube be necessary the flow rates specified in Table IX of EN 60529 shall be used.

5.3.5 Washing

The parts of the head protector included in the manufacturer’s washing instructions shall be washed five times according to ISO 6330 Textiles - Domestic washing and drying procedures for textile testing. The washing program shall be chosen according to the washing instructions on the neck protector. The test laboratory may decide that a removable cover does not need to fulfil this requirement.

5.4 Determination of area to be protected

The head protector is placed on an EN 960 headform of appropriate size mounted on a shoulder dummy, see figure 1, and inflated. During inflating the head protector is filmed using a high speed camera and it is determined if the head protector covers the prescribed area to be protected. The camera shall be positioned so the central axis of the camera lens is level and perpendicular to the central longitudinal plane of the headform. The centre of the lens shall be aimed at the intersection of the A-plane and the central vertical axis.

NOTE: It is recommended that two cameras are used for the test to avoid an incorrect evaluation during the test due to an asymmetric positioning of the inflated head protector. The cameras should be positioned on each side of the headform.

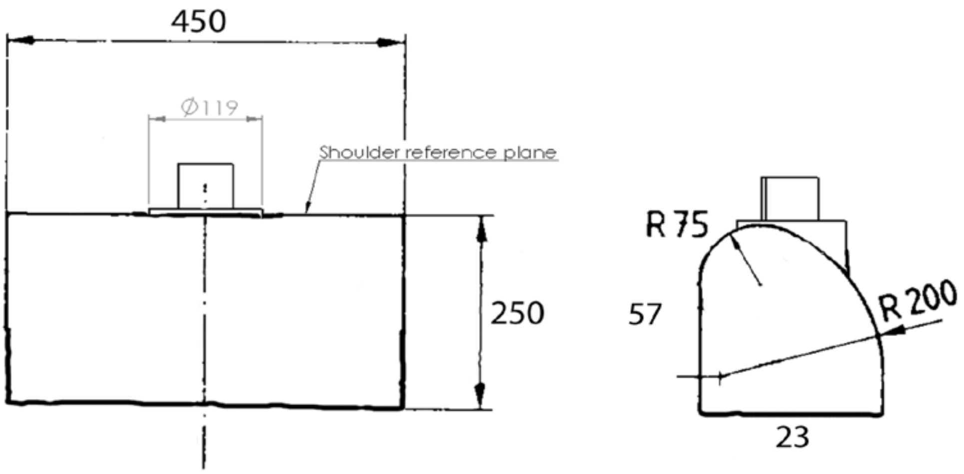

Figure 1. Shoulder dummy

Table 2. Height of headform reference plane

Circumference of the headform at the AA' plane	Distance shoulder reference plane to headform reference plane (mm)
495	165
535	172
575	182
605	188
625	191

5.5 Determination of shock absorbing capacity

5.5.1 Apparatus

The apparatus shall be in accordance with EN 13087-2, 5.3, falling headform method.

The anvils shall be in accordance with EN 13087-2, 5.3.2.2 except for the diameter of the flat anvil, which shall be (300 ± 3) mm, and the length of the kerbstone anvil which shall be no less than 300 mm.

5.5.2 Headforms

The headforms to be used shall comply with EN 960. See table 1. At the request of the manufacturer, the test laboratory may choose to use a supportive device, i.e. simulating a neck/shoulder, provided that the mass requirements of EN 960 are still fulfilled.

5.5.3 Test area

The test area is given in Figure 2. Measurements for different headform sizes are given in Table 3.

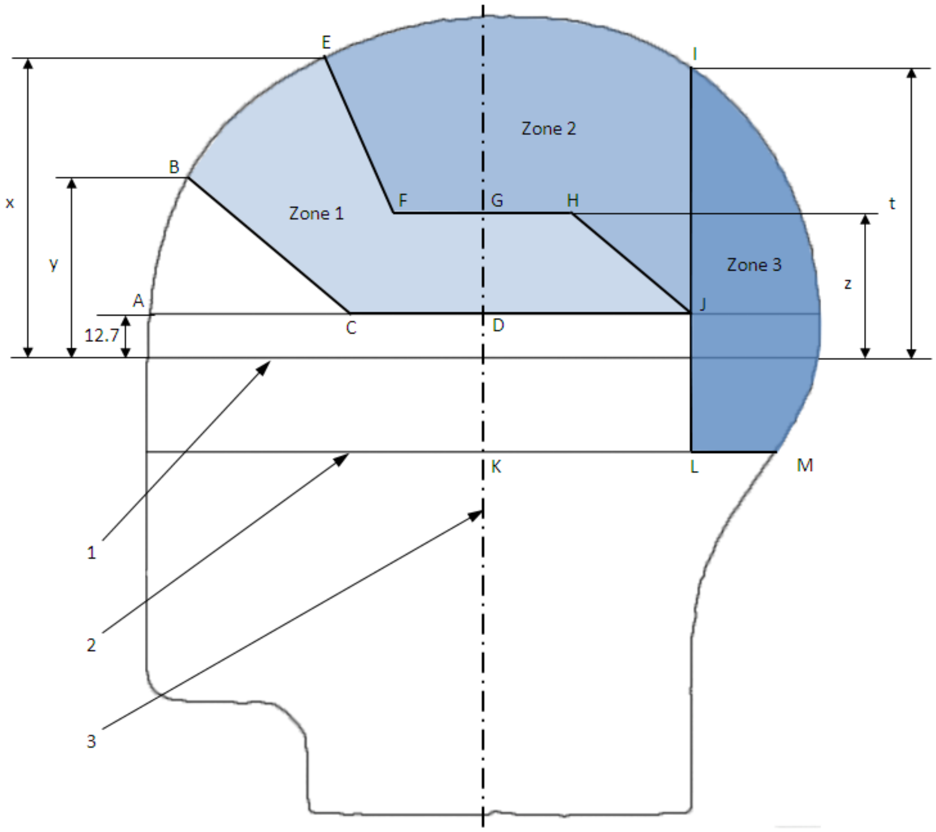

Figure 2 Test area

Key
1 reference plane
2 basic plane
3 central vertical axis

Table 3 – Headform measurements.

Size designation (EN 960)	x	y	z	t	CD	DJ	FG	GH	KL
535	83	55	46	81	29	59	27	18	60
575	90	59	50	86	30	63	29	18	65
Dimension in millimeters. NOTE The dimensions CD, DJ, FG, GH and KL correspond to the length of the chords measured with dividers.									

5.5.4 Procedure

5.5.4.1 Testing parameters

The testing shall be carried out on room conditioned head protectors.

The head protector shall be tested in inflated condition. The pressure shall be the working pressure as specified by the manufacturer.

The headform sizes in table 3 shall be used. For head protectors not covered by these headforms use the nearest smaller headform, e.g. a size 525 mm head protector shall be tested using a 495 mm headform. When the head protector covers more than one headform size, the largest headform within the stated size range shall be used for the tests.

Where a head protector size covers more than one headform size or where more than one headform size is considered appropriate by the test house then the test house will use the reserve samples to test on the different headform size.

Fit the head protector to the headform in the manner in which it is intended to be worn on the head, see manufacturer’s instructions, and position the assembly so as to present the specified impact point over the centre of the anvil. The centre of gravity of the headform shall be positioned along the central vertical axis of the anvil. In addition, if possible, the impact point on the helmet should be tangential to the anvil surface. Raise to the required drop height and release. Impact each head protector on one site. However the manufacturer may choose to perform the two impacts on the same sample thereby reducing the number of samples needed for the test.

The testing shall be carried out in accordance with table 4 below.

Table 4 – Test parameters.

Sample number	Anvil	Zone
1	Kerbstone	1
2	Flat	1
3	Flat	2
4	Kerbstone	2
5	Kerbstone	3
6	Flat	3

The velocity of the headform shall be in accordance with table 5 below.

Table 5 – Headform velocity at the shock absorption test.

	Flat anvil	Kerbstone anvil
Zone 1	4.53 +0.1/-0 m/s	3.68 +0.1/-0 m/s
Zone 2	5.42 +0.1/-0 m/s	4.57 +0.1/-0 m/s
Zone 3	5.81 +0.1/-0 m/s	4.57 +0.1/-0 m/s

The velocity of the headform shall be measured at a distance between 60 mm and 10 mm prior to impact, to an accuracy of 1 %.

The testing shall be conducted under conditions of room temperature.

5.5.4.2 Recording

The measured results (a_{max}) shall be recorded in tabular from completed with time/acceleration diagrams.

The extent of any damage as described in 4.16 shall also be recorded.

5.6 Determination of activation time

This test can be performed simultaneously as the tests described in 5.4, 5.7, 5.8 and 5.12.

The head protector is placed on a shoulder and head dummy and deployed. During inflating the head protector is filmed using a high speed camera (minimum 500 frames/s). During inflating also measure the pressure in the head protector and record the time between deployment and inflated status. This time corresponds to the activation time. The pressure gauge shall have a rise time < 1 ms.

5.7 Duration of inflated status

The pressure shall be measured by a pressure gauge during the duration of inflated status. The pressure gauge shall have a rise time < 1 ms.

5.8 Temperature exposure evaluation (applicable only for hot gas generators)

The temperature is detected with a fast answering thermometer (e.g. digital thermometer with flat probe of low mass).
The protector is conditioned at standard ambient temperature (see 5.2).
The probe of the thermometer shall be fixed on the potential skin contact surfaces identified in 4.7. If more than one surface requires testing, multiple probes or multiple inflations should be used. The probes can be fixed with suitable means (e.g. adhesive tapes, elastic strips etc.).
The protector is activated and the temperature is detected from 0 s to 15 s after starting the inflation, by recording it continuously or at least every 3 s. The temperature exposure is the average value.

5.9 Evaluation of the function of the triggering system

5.9.1 Test equipment

5.9.1.1 Test dummy

Test dummy in accordance with 49 CFR, Part 572. The dummy shall be a Hybrid III 50 percentile male.

5.9.1.2 Test person

The test persons shall have a height, weight, head circumference and any other limitations in accordance with the manufacturer's instructions for use. Any test person(s) shall be selected by the test laboratory.

During the tests the test person shall use a protective helmet. It is recommended that the helmet used during the test has a thickness as close as possible to the thickness of an inflated head protector.

5.9.1.3 Test bicycle

The test bicycle shall have a height, weight, rim size and any other limitations in accordance with the manufacturer's instructions for use.

5.9.1.4 Kerb

Obstacle simulating a kerb with the height (150 ± 10) mm and a minimum length of 1 m. It shall be made of steel and shall be rigidly mounted to the test track in an angle of (50 ± 5) °.

5.9.1.5 Car dummy

Body simulating a moving car. The body shall be in accordance with Figure 3. The part of the body simulating the car front shall be rigid and made of steel. When testing, the lower part of the chassis shall be 250 mm above the ground level. The weight of the car dummy, including (if applicable) guidance system, shall be ≥ 1000 kg.

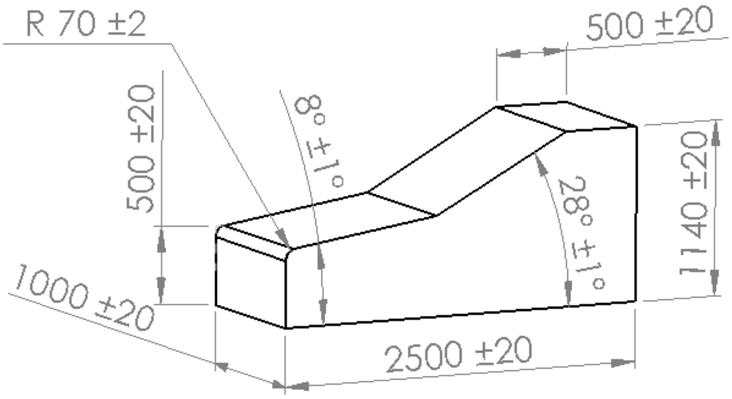

Figure 3. Car dummy

5.9.2 Test procedure

During the tests below, care must be taken to insure that the test dummy does not shift on the bicycle. These precautions must not influence the test dummy’s movements during impact. The tests 1-6 can be performed in any order but tests 1-4 shall be performed using samples 13-16 and tests 5 and 6 using samples 17 and 18.

Test 1: A test dummy mounted on a test bicycle is hitting a kerb with a (50 ± 5) ° angle between the kerb and the longitudinal axis of the bicycle. The impact speed shall be (20±2) km/h.

Test 2: A test dummy mounted on a test bicycle is hit by a car dummy from behind. The impact speed shall be (20±2) km/h.

Test 3: A test dummy mounted on a test bicycle is hit by a car dummy at a 90° angle (side impact). The impact speed shall be (20±2) km/h.

Test 4: A test dummy mounted on a test bicycle experiences a complete lock-up of the front wheel. This can be simulated by hitting a solid obstacle higher than the center of the front wheel or with a stick attached to the front wheel causing a complete stop of the rotation of the wheel. The impact speed shall be (20±2) km/h.
Tests 5 and 6: Each of the head protectors with indicator used for the test in 5.13 shall be tested according to one of the tests (1-4) specified above. The test laboratory chooses which tests.

The test laboratory may choose to perform one or more of the tests using test person(s) instead of the test dummy. In this case head protectors are used where the airbag and gas generator are replaced with means to indicate accident detection.

Determine whether the head protector inflates, i.e. has reached its working pressure, before head impact. To evaluate whether working pressure is reached a comparison is made between the high speed sequences from this test with those made when testing according to 5.6.2. If the tests are performed using test persons with indicators, measure the time between accident detection and head impact. The indicators shall be clearly visible, such as LED indicators, and/or audible. Head impact is defined as when the surface of the test person’s helmet impacts the ground. All tests shall be evaluated using a high speed camera using a frequency of at least 500 frames/s.

5.10 Drop test

The head protector is allowed to fall onto a drop test plate from a height of 2 m. The drop test plate shall be made of steel or concrete or a combination of these materials and have a mass of at least 500 kg. Five drops shall be performed. At least one of the tests shall be directed towards the gas generator and one shall be directed towards the circuit breaker. The test shall be performed on an inactivated, ambient conditioned head protector. After the test the function of the head protector is tested in accordance with 5.9.

5.11 Acoustic test

The head protector is fitted to a test dummy according to the manufacturer’s instructions. The test dummy shall be a Head and Torso Simulator (HATS) in accordance with IEC60959 or ANSI S3 36-1985. Sound level meters according to EN 61672-1, class 1 shall also be used. Deploy the head protector and measure the sound level.

5.12 Function test following conditioning

Four head protectors are tested. The head protector is placed on a headform and shoulder dummy combination (see 5.4) and positioned according to the manufacturer’s instructions. The head protector is deployed and the pressure generated by the gas generator is measured and recorded for each test. The pressure gauge shall have a rise time < 1 ms. The head protector shall be deployed within 2 minutes from removal from the conditioning chamber.
Prior to the test, the head protectors shall be conditioned in accordance with 5.3 and with the table below. Except for the 48 h UV conditioning, the head protectors shall be activated during the conditioning. The test is documented by a high speed camera (minimum 500 frames/s).

Table 6 – Sequence of tests and number of tests per sample

Sample no.	Conditioning
1	50° C
2	-20° C
3	Aged
4	Ambient

5.13 Resistance to false accident detection during normal bicycling

5.13.1 Test equipment

5.13.1.1 Test persons

The test persons shall have a height, weight, head circumference and any other limitations in accordance with the manufacturer’s instructions for use.

Any test person(s) shall be selected by the test laboratory.

5.13.1.2 Test bicycle

The test bicycle shall have a height, weight, rim size and any other limitations in accordance with the manufacturer’s instructions for use.

> NOTE: It is recommended that the bike should have a brake for the back wheel which is applied by pedaling in reverse. The bicycle should also have a speed tracking computer mounted.

5.13.1.3 Markers

16 road cones to act as markers.

5.13.1.4 Kerbstone

A raised dais to act as a kerbstone mock-up. It shall have a height of 80 ± 10 mm and the length shall be at least 3000 mm long. It is recommended that this kerb mock-up is made out of some wooden material to facilitate simple setup.

5.13.1.5 Head protector with indicator

For the test, head protectors are used where the airbag and gas generator are replaced with means to indicate accident detection. The indicators shall be clearly visible, such as LED indicators, and/or audible.

5.13.2 Procedure

5.13.2.1 Test track specification

Two test persons, using a specified test bicycle and head protectors with indicator (see 5.1), shall carry out all the test track sections below. Each test person shall run the test track at least twice, exchanging head protectors with each other after each test track sequence. The sections may be performed sequentially or individually and in any order. Unless otherwise specified below, the speed of the bike shall be 14 ± 4 km/h.

5.13.2.1.1 Serpentine course

Using the road cones, a serpentine course should be laid out. The first eight cones shall be placed with a distance of 2.5 m between them, the following eight with a distance of 2 m between them. The cones shall be placed in a straight line. The test person shall traverse the course by riding the bike in a slalom pattern between the cones, the first part of the course with the speed specified above and then with a speed adjusted to be able to deal with the sharper turns.

This test shows tolerance to sharp turns and attempts to simulate the avoidance of obstacles in the road.

5.13.2.1.2 Acquiring high speed and breaking hard

This test shall be done twice, once while standing up while pedaling and once while sitting down. The test person shall reach a speed of not less than 25 km/h and then breaking as hard as possible.

5.13.2.1.3 Bending of body

The test person shall bend the upper part of the body back and forth three times, first in a front-back direction and then sideways. The test subject shall be pedaling during the entire movement.

5.13.2.1.4 Rotation of body

The test person shall rotate the upper body, i.e. head and shoulders, three times from straight forward to 90 degrees right and then to 90 degrees left and back to a straight forward direction. This simulates a somewhat exaggerated ocular inspection of the surroundings. The test subject shall be pedaling during the entire movement.

5.13.2.1.5 Checking the chain while riding

The test person shall bend down three times to check the status of the bicycle’s chain while travelling at the above specified speed.

5.13.2.1.6 Riding up and down a kerb

The kerb mock-up shall be placed in the path of the test person’s bicycling track, whereupon he/she shall ride the bike up on the kerb and then down on the other side.
This test shall be done twice; once when riding the bike against the kerb without lifting the wheel at all, simulating a kerbstone encountered without being prepared, and once when lifting, or jumping with, the front wheel so that it lands on the dais without hitting the kerb edge.

5.14 Function indicator

Following the manufacturer’s instructions, activate the head protector and verify that the indicator is clearly visible and audible. The warning signal is tested by draining the battery until the warning signal indicates and then a further 55 minutes. After this the head protector is deactivated. The head protector shall be reactivated a maximum of 5 minutes prior to testing according to 5.9.

5.15 Wear resistance test

5.15.1 Test equipment

A suitable test equipment is shown in EN 13595-2, clause 4.2 but conforming to the following characteristics:

- Belt speed (0.4 ± 0.05) m/s
- Belt grit OP 60
- Abraded area 1963 mm^2
- Static force on sample 98 N
- Static pressure on sample 50 kPa
- Drop height 50 mm

5.15.2 Procedure

Mount the test specimen on the sample holder over two layers of cotton denim and one layer of thin leather (see EN 13595-2:2002, Figure 3). To measure the time, one trigger wire is attached below the test specimen and one above. The pendulum is supported by the release mechanism so that the face of the test specimen is 50 mm ± 5 mm above the abrasive grit belt.
Start the belt. The pendulum is released and the test specimen is abraded to perforation, as signalled by the cutting of the trigger wire between the test specimen and the denim. Raise the pendulum immediately and record the time between the cutting of the two trigger wires to the nearest 0.05 s.

5.16 Blocked deployment test

5.16.1 Test equipment

A test dummy in accordance with 5.9.1.1 shall be used. The dummy shall be equipped with a lower neck load cell with a capacity of at least 14 kN in the Z axis (Fz). The head of the test dummy shall be replace by a metal plate with the following dimensions:

Thickness: ≥ 4.5 mm
Width: ≥ 200 mm
Length: ≥ 400 mm

The steel plate shall be mounted to the neck of the dummy so that the rear edge of the plate shall be ≥ 250 mm from the centre of the dummy's neck.

5.16.2 Procedure

Place the head protector to the neck of the dummy in accordance with the manufacturer's instructions. Deploy the head protector and register the force measured by the load cell in the Fz direction. Repeat the test on two further samples (see table 1).

6 Marking

Inflatable head protectors shall be permanently and conspicuously marked with at least the following information:

a) the number of this test method;
b) the name or trade mark of the manufacturer or his authorised representative in the European Union or country where the product is placed on the market;
c) identification of the product type, commercial name or code;
d) the size designation of the item;
e) The „***i***“ in a book pictogram ISO 7000-1641 shall be used. The pictogram shall be placed on the product and on the package in which it is supplied.

7 Information to be supplied by the manufacturer

Inflatable head protectors shall be supplied with information and instructions for fitting, use and maintenance. These are an essential part of the protective equipment. They shall contain at least the following information in the official language(s) of the state or region in which they are placed on the market:

a) the name and address of the manufacturer or his authorised representative;
b) the type of use for which the protectors are intended including any relevant restrictions;
c) the hazards specific to bicycling against which some protection is given;
d) the hazards specific to bicycling against which protection is not given;
e) all the information required in clause 6 „Marking“;
f) guidance on how to adjust the protector;
g) warnings and limitations of use, including the following arguments:

- no protector can offer full protection against injury;
- the protector may not provide protection to the user under all circumstances, especially:
    1. that there is no protection against a direct hit to the head;
    2. that the head protector offers limited protection against pointed objects;
    3. accident situations where the protector offers limited protection
- the compatibility or not with other devices and garments;
- if applicable, the warning that protection provided will be impaired if the garment is not closed;
- a warning about any contamination, alteration to the protector, or misuse that would dangerously reduce the performance of the protector;
- any limitations concerning the user such as height, weight or head circumference.
- any limitations concerning the bicycle such as height, weight or rim size.

h) instructions concerning periodical checks of the whole device or its specific components;
i) information on the selection of the correct size of the device;
j) a declaration concerning the absence of harmful substances which could come into contact with the user;
k) instructions for care and cleaning. Use international care label symbols, including negative labels, if applicable;
l) instructions concerning inspection and resetting, if applicable, of the protector, when to replace it and how to decide if it no longer provides adequate protection;
m) instructions for the safe disposal of the protectors, in accordance with European regulations, and of any hazards that could arise during mechanically disrupting or incinerating the product.

Annex A
(informative)

Relationship between this test method and the Essential Requirements of EU Directive 89/686/EEC

Essential requirements of Directive 89/686/EEC, Annex 2	**Clauses/subclauses of this method**
1.1. Design principles 1.1.1.Ergonomics (general)	4.2, 4.15
1.1. Design principles 1.1.2.Levels and classes of protection	N.A.
1.2. Innocuousness of PPE 1.2.1. Absence of risks and other 'inherent' nuisance factors	4.10
1.2. Innocuousness of PPE 1.2.1.1. Suitable constituent materials	4.1.1
1.2. Innocuousness of PPE 1.2.1.2.Satisfactory surface condition of all PPE parts in contact with the user	4.1.1, 4.7
1.2. Innocuousness of PPE 1.2.1.3.Maximum permissible user impediment	4.2
1.3. Comfort and efficiency 1.3.1. Adaptation of PPE to user morphology	4.2
1.3. Comfort and efficiency 1.3.2. Lightness and design strength	4.2
1.3. Comfort and efficiency 1.3.3. Compatibility of different classes or types of PPE designed for simultaneous use	N.A.
1.4. Information supplied by the manufacturer	6, 7
2.1. PPE incorporating adjustment systems	N.A.
2.2. PPE 'enclosing' the parts of the body to be protected	N.A.
2.3. PPE for the face, eyes and respiratory tracts	N.A.
2.4. PPE subject to ageing	5.3.4, 7
2.5. PPE which may be caught up during use	N.A.
2.6. PPE for use in explosive atmospheres	N.A.
2.7. PPE intended for emergency use or rapid installation and/or removal	N.A.
2.8. PPE for use in very dangerous situations	N.A.
2.9. PPE incorporating components which can be adjusted or removed by the user	N.A.
2.10. PPE for connection to another, external complementary device	N.A.
2.11. PPE incorporating a fluid circulation system	N.A.
2.12. PPE bearing one or more identification or recognition marks directly or indirectly relating to health and safety	6
2.13. PPE in the form of clothing capable of signaling the user's presence visually	N.A.
2.14. 'Multi-risk' PPE	N.A.
3.1. Protection against mechanical impact 3.1.1. Impact caused by falling or projecting objects and collision of parts of the body with an obstacle	4.4, 4.5, 4,6, 4.8
3.1. Protection against mechanical impact 3.1.2. Falls	N.A.

3.1. Protection against mechanical impact 3.1.3. Mechanical vibration	N.A.
3.2. Protection against (static) compression of part of the body	N.A.
3.3. Protection against physical injury (abrasion, perforation, cuts, bites)	4.13, 4.14
3.4. Prevention of drowning (lifejackets, armbands and lifesaving suits)	N.A.
3.5. Protection against the harmful effects of noise	N.A.
3.6. Protection against heat and/or fire	N.A.
3.7. Protection against cold	N.A.
3.8. Protection against electric shock	N.A.
3.9. Radiation protection	N.A.
3.10. Protection against dangerous substances and infective agents	N.A.
3.11. Safety devices for diving equipment	N.A.

Annex B
(informative)

Description of changes made in the different versions

In version 2:4 of this document the time requirement specified in *4.12 Wear resistance* has been corrected to at least 1.00 s.

In version 2:5 of this document the belt speed specified in *5.15 Wear resistance test* has been corrected to (0.4 ± 0.05) m/s.

In version 2:6 of this document the following changes have been made:

- 5.3.4 – The alternative water exposure method has been changed.
- 5.4 – A new Figure 1.

In version 2:7 of this document the following changes have been made:

- 3.1.5 – *Head protector* has been replaced by *headform*.
- 5.3.4 – In the alternative water exposure method the exposure times have been adjusted to 110 minutes (was 105 minutes) and 10 minutes (was 15 minutes).
- 5.4 – The camera positioning has been more specified.
- 5.9.2, Test 1 - *Front wheel* has been replaced by *longitudinal axis*