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The development of next generation test standards for helmets.

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ABSTRACT

Injury statistics show that accidents with a head impact often happen with an angle to the impacting object. An angled impact will result in a rotation of the head if the friction is high enough. It is also known that the head is more sensitive to rotation than pure linear motion of the head. CEN has initiated the work to design a new helmet test oblique or angled impact test method a helmet test method that can measure the rotational energy absorption in a helmet during an angled impact. This paper presents a short summary of possibilities and limitations on how to build a helmet test method that can measure the rotational energy absorption in a helmet during an angled impact.

Keywords: helmet, impact, oblique, test method, angular acceleration

NOMENCLATURE

TBI Traumatic Brain Injury
DAI Diffuse Axonal Injury
SDH Subdural hematoma
MIPS Multi-directional Impact Protection System

INTRODUCTION

The most common injuries in motor and sport activities are injuries to the head. The best way to protect the head is to wear a helmet. Sports and automotive helmets are today tested only for pure radial impacts to the helmet, except for the BS 6658 and EN 22.05 oblique impact test for MC helmets. A radial impact is however not the most common impact situation according to injury statistics and accident reconstructions, which show that an oblique impact is more frequent (Aare et al. 2003, Otte et al. 1997, Verschueren 2009, Bourdet et al. 2012, Mellor and Chin 2006). The number of epidemiological studies including the direction of impact, speed and location on the helmet is few. The studies mentioned above do only give a first estimation of the impact speed and direction of impact to motorcycle, equestrian and bike accidents. As the head is more sensitive to angular motion than translational motion it is important to investigate if a test method can include a tangential component (Holbourn, 1943, Gennarelli et al., 1987; Kleiven, 2006).

A recent summary report from a sport helmet symposium presented the synthesis of information and opinion from a range of presenters and disciplines (McIntosh et al. 2013). It was concluded that there is a need to develop new test methods for helmet including an oblique impact test. McIntosh et al.concluded that there are a number of parameters that need to be evaluated before a new oblique test could be defined. The performance criteria mentioned by McIntosh et al. was: biofidelity of the head (size, shape, mass, inertia, helmet fit and restraint fit), repeatability, robustness, reliability and validity (use of appropriate injury criteria considering combinations of angular and linear kinematics, impact force, direction and location).

There are several publications on how to design a method to measure the energy absorption in an oblique impact with a significant tangential force acting on the helmet. Aldman et al. (1978) presented a method with a spinning concrete wheel that was used to drop helmets on. Halldin et al. (2001) and Mills and Gilchrist (2008) presented methods where the head was dropped on a sliding steel plate in order to result in an oblique impact. Pang et al. 2012 presented a method similar to the method by Halldin et al.but with the addition of a HIII neck and also the possibility to measure the force on the plate. Other ways to test helmets for oblique impacts are to drop the helmet to an angled surface (Finan et al. 2008, Deck et al. 2012).

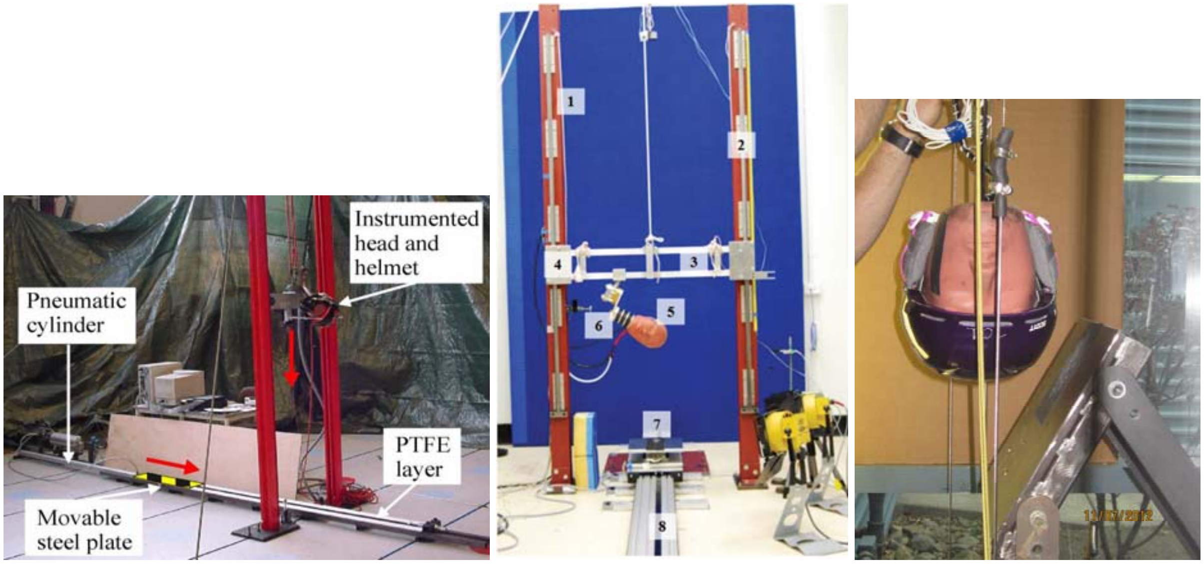

Figure 1. Different oblique test methods. Aare et al 2013, Pang et al. 2011 and photo of angled impact surface.

The results from different experimental studies including an angled impact show that it is possible to measure the energy absorption and differentiate helmets that will absorb the rotational forces better from helmets that show less good energy absorption (Halldin et al. 2001, Aare et al. 2003, Finan et al. 2008, Hansen et al. 2013, Phillips 2013). Figure 2 shows results from a benchmark study on ski helmets performed in the test rig by Aare et al. in Sweden. The helmets were dropped from 0.7m. This results in a vertical speed of approximately 3.7 m/s. The horizontal speed is set to 6.4 m/s, resulting in an impact speed of 7.4 m/s and an impact angle of approximately 30 degrees. Six ski helmets from the market called A, B, C, D, E and F was compared to three helmets A, B and C also from the market but with the MIPS technology installed. The Multi-directional Impact Protection System (MIPS) was inspired by the human head and allows the outer helmet shell to move relative to the liner in the interior. This is just to exemplify that: 1; There is A wide spread in the measured data from different helmets and 2; that there are potential to increase the energy absorption in an oblique impact. The MIPS helmet presented here should be seen as one example on how to reduce the energy transmitted to the brain. There are other examples of technologies that can reduce the angular acceleration (Hansen et al. 2013 and Phillips 2013).

The results from these studies have also raised questions about how to design a test method that should be robust, inexpensive and reproducible. There are discussions on how to fixate the head to the helmet in an oblique impact. How hard or loose should the helmet be fixated to the head. Another question is whether the neck as a boundary condition to the head is needed in the test.

The helmet manufacturers aim to produce the helmet that consumers want. The helmets sold to the market today are sold more or less on design, weight and comfort. Safety is not a real argument. One reason is that the approval tests are not really discussed and understood by the dealer or the end consumer. It is therefore also important to use test methods that are realistic and gives the helmet manufacturers new goals to achieve in the struggle to improve the energy absorption in the only safety barrier that is between the brain and the obstacle. It should however be stressed on that the most important is that people wear a helmet. A new test method should not result in too expensive helmets.

Within the European Committee for Standardization (CEN) TC158 (Head protection) the work has initiated to design a new test method for helmets in general. CEN TC158 has been working on this topic in the past without any concrete results like a new standard. One reason for that the work has started again is that the knowledge about head injury biomechanics has come to a new level, very much depending on more sophisticated experimental and numerical simulations of real impact scenarios.

This paper presents a short summary of the initial work within CEN TC158 and also the possibilities and limitations on how to build a test that can measure the rotational energy absorption in a helmet during an angled impact.

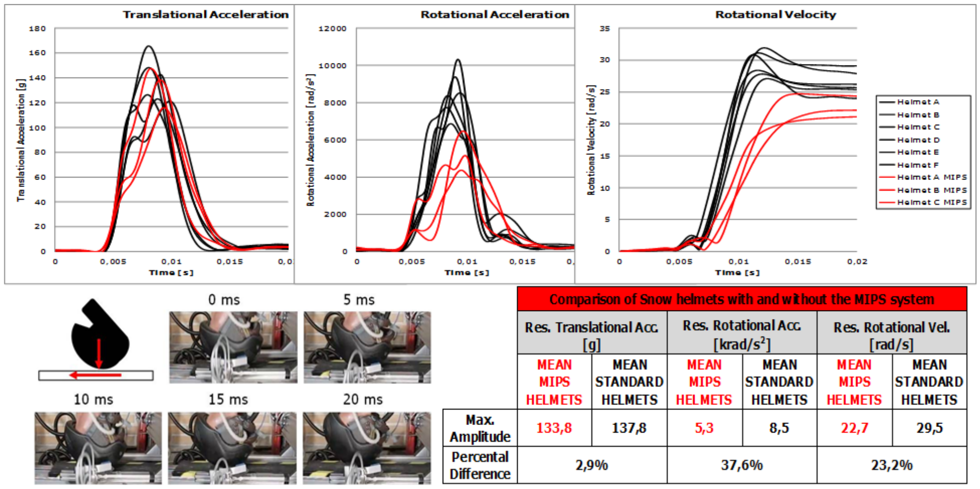

Figure 2. Benchmark Ski-helmets.

REQUIREMENTS FOR AN OBLIQUE HELMET IMPACT TEST

In this section the fundaments will be defined for a new test method to measure rotational energy absorption in impacts including a tangential force. In order to design a new test method for homologation tests of helmets used worldwide the following basic requirements need to be fulfilled:

- Simple, robust and cost effective.
- Impact conditions based on real accident data.
- Adjustable for several helmet segments.

CEN TC158 (Working group 11) has the following subtasks defined in order to design the new test method, Figure 3. The subtasks are not fixed and more tasks will probably be added. Below are most of the tasks addressed and discussed. No final suggestions are made, but it is important to spread information regarding the work within WG11 in order make the best possible test method in place.

A. *IMPACT SPEED AND ANGLE*

The goal is that the test should be designed for each helmet segment. The typical speed, angle and impact surface can vary within each sport and activity in unlimited ways. There are anyway a number of studies published that could give estimation for different impact situations for each helmet segment. Table 1 presents accident reconstruction studies for bike, MC, equestrian and ski (Super-G and Down-hill).

A normal drop tower has limitations regarding the height which makes it difficult to test helmets above 10m/s. To design a test method that can be used for all helmet segments might be difficult as the impact speed for some helmet segments would need a drop tower higher than 10 m.

The impact angles presented in Table 1 are between 20-60 degrees (0 degree is if you are lying on the floor and 90 degrees is how helmets are normally tested today). The question is if the impact angle should be chosen based on accident reconstruction studies or if the impact angle should be chosen in order to introduce as much tangential force as possible. Here it is not meant that a test should be designed with the goal of a high tangential force in a sport where it is not evident. The test should measure the rotational energy absorption in the helmet. If the angle is too steep the helmet will just slide on the impact surface and that will not evaluate the helmets possibility to absorb the rotational energy, (Mills et al. 2009, Ghajari et al. 2012). The angle should probably be between 30-45 degrees in order to result in a normal force between the helmet and the ground large enough to avoid slippage. As Mills et al. present the slippage is very much dependent on the normal force component, the coefficient of friction between the head/helmet and helmet/plate and the total inertia of the head and the helmet.

TABLE I. IMPACT SPEED AND ANGLE FOR MC, EQUESTRIAN, BIKE AND SKI HELMET FROM ACCIDENT RECONSTRUCTION STUDIES.

Helmet	Reference	Speed (m/s)	Angle (Degree)	Surface
MC	Otte et al. 1999	12	<30	Side of a car or the road
Equestrian	Mellor and Chinn 2006	9	37	Hard grass
Bike	Verschueren 2009	5,3	40	road
	Bourdet et al. 2012	6,8	60	car
Ski (DH and Super-G	Inhouse report.	19	21	Hard snow/ice

The impact surface is another subject that needs to be evaluated both for the stiffness and the coefficient of friction. The impact surface for MC and bike helmets should probably be hard like a steel plate covered with grinding paper. In a sport like equestrian the impact surface should mimic hard grass or turf (Forero Rueda 2009). However, an impacting surface that is deformable might be difficult to control or expensive. The final solution might be to use a stiff surface and reduce the

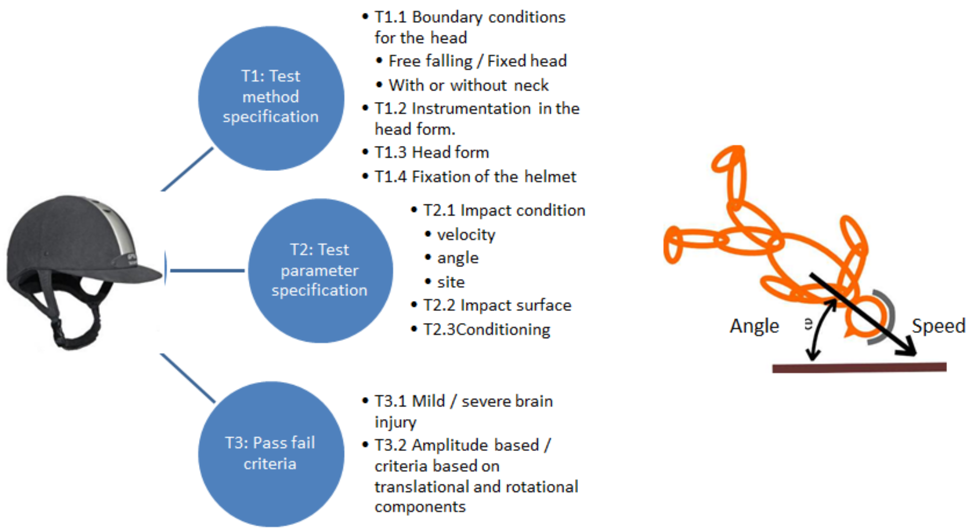

Figure 3: Shows the tasks that need to be addressed when designing a new oblique test method.

impact speed to get a shell deformation that is realistic for an equestrian accident. For snow helmets the impact surface could be everything from a hard ice surface, a rock or soft snow. It is clear that both stiffness and coefficient of friction differs allot between these materials.

B. *TEST METHOD DESIGN*

There are many ways to design a test method for an oblique/angled impact as shown in Fig. 1. There are two existing test methods as presented in (UN ECE reg. 22-05, Methods A) for MC helmets. Test method A is designed in order to measure the tangential force between the helmet and the impacting plate that is angled 15 degrees. The idea of dropping the helmet at an angle is tempting as it is simple with just one part moving, the helmeted head. The simplicity of measuring the tangential and the normal force in the plate is interesting as it is a cheap solution instead of having a number of accelerometers and/or rotational transducers. However, it has not been shown that the tangential force in the plate can measure the energy absorption in the helmet as accelerometers in the head form can do (Mills et al. 2009). A possible improvement of the test used in ECE 22-05 is to change head form used and install accelerometers or a combination of translational accelerometers and rotational transducers. Deck et al. 2012 presented a proposal for a new test method for Bike helmets where the helmet should be dropped onto a 45 degree angle. Deck proposed to use the HIII neck in the test.

One benefit of a test method using a vertical drop onto an angled surface is that it can be installed in most test institutes with minor changes. The existing drop tower can be used if the drop height is below 5 m.

Another method is as presented by Halldin et al. (2001), Mills and Gilchrist (2009) and Pang et al. (2011) to drop the helmet against a plate that is accelerated to a controlled speed. This design has its benefits as well as limitations. The benefit is that it is easy to set different combinations of impact speeds and impact angles. One limitation is that the test is more complex and therefore more expensive compared to a drop against an angled surface.

A third test method is the one developed by NOCSAE where a linear impactor is accelerated by a pneumatic cylinder to hit the center of gravity in the dummy head (NOCSAE 2006). The dummy head is positioned on a Hybrid III dummy neck. The impactor is equipped with curved plastic surface to mimic a helmet to helmet hit (Designed for American football or ice hockey helmets). The test designed by NOCSAE is currently modified adding measurements for the angular acceleration and also an initial off-set to introduce more rotation in the test than in the test set up designed by NOCSAE (Rousseau et al. 2011). The test set-up proposed by Rousseau is designed for ice hockey helmets and results in an impact with a minor tangential component which makes the test less effective to analyze the rotational energy absorption in a helmet. It is however possible to design the NOCSEA so that a larger tangential component is introduced.

So, there are several methods to introduce tangential force to the helmet and also measure the energy absorption in the head. The question is which method will reach the demands on robustness and low cost.

But before deciding on which test method to be used the following questions need to be addressed:

- Boundary condition for the head
  - Do we need the neck as a boundary for the head?
  - How to control the fixation of the helmet on the head?
- How to control the impact location?
- Injury thresholds or pass/fail criteria.

C. *BOUNDARY CONDITION FOR THE HEAD*

In current test methods the head is either falling unrestrained onto the impact surface (European test standards) or constrained to a monorail through a rigid arm attached to the head (US test standards). This can be said to be two extremes. Between these extremes is the normal situation where the head is constrained by the human neck. In order to design an oblique test method there are questions if the neck will affect the measured translational and angular accelerations in the dummy head. It is clear that the head is restraint by the neck and at some time will rotate around a point in the neck or even lower down in the thoracic region. Earlier studies like the COST 327 study has shown that the amplitude of the angular acceleration is affected by the neck (COST327 2001). Helmeted full body Hybrid III dummies were dropped on an angled surface and compared to free falling helmeted head forms. The results showed that the angular acceleration differed in amplitude by about 20%. Bausenberg et al (2001) presented a numerical study on helmet to helmet impacts simulating an American football accident. It was concluded that the neck changed the characteristics of the angular acceleration comparing impacts with and without a neck. Ghajari et al. 2012 showed that the angular acceleration components could differ as much as 40% comparing a helmet impact with the full body and the head only. In this study Ghajari used the THUMS model and simulated an oblique impact on the lateral portion of the helmet. Ghajari proposed to change the inertial properties of the head in order compensate for the neck and the body if using the head only in an oblique impact test.

Forero 2009 reconstructed 12 jockey accidents using MADYMO. Two of these where studied in detail simulating with and without the body in a helmet to racetrack turf. The angular acceleration was increased from 6462krad/s2 to 10104krad/s2 in one case and from 5141krad/s2 to 6444krad/s2 in the second case comparing the simulation with a complete body and a simulation with the head only. It was mentioned in this study that the MADYMO human body model has an unrealistic representation of the flexibility in the vertebral joint representation that could have resulted in this large difference.

Verschueren et al. 2009 performed reconstruction of 22 bike accidents using MADYMO. Nine of the accidents were simulated with the head only and also with the complete body. The result from this study showed that the correlation between the angular acceleration between the head only and the simulation with the complete body correlated *well* for four of nine reconstructions. The correlation was defined as *medium* for three and two out of nine were defined as *bad* with a difference of about 30% for one example which was defined as bad.

The duration of impact time is different in the jockey accident against the racetrack turf (8-20 ms) and the bike accidents against a hard road (5 ms). If a test should be designed with a surface mimicking a racetrack turf for Jockey helmets a neck might be demanded. Forero also mentioned that absence of the neck and the body might result in that the direction of the acceleration is altered.

It is therefore possible that there are impacts against harder surfaces where the neck does not have time to affect the head during the time of impact.

The conclusion that can be made here is that the neck in general affects the motion of the head. It can also be argued that a test method could be defined with impact angles where the affect of the neck is less during the short time (5-10ms) when the helmet has contact to the impacting surface.

The main reason to define a test method without a neck is to make the test simpler and less expensive. If this is the case and impact directions are chosen where the neck affect the angular acceleration this need to be taken into account in the test either by:

- The proposal by Ghajari et al. (2012) where the head inertia is scaled to take the boundary forces from the neck into account.
- To scale the pass/fail criteria.

One reason to include the neck like the HIII neck is that it makes the fixation of the head easier and more controlled as proposed by Pang et al. 2011. The HIII neck is on the other hand known to be too stiff and not validated to volunteer or cadaver experiments except for pure frontal impacts in 11m/s. Other experimental necks should also be considered like the THOR (Haffner et al. 2001) or the MATD (Whithnall and Fournier 1998)

The other boundary condition that needs taken into account is fixation of the helmet to the head. Mills and Gilchrist (2008) performed oblique tests on bicycle helmets using a HII head equipped with an acrylic wig to mimic the hair and scalp. Aare and Halldin (2003) also performed tests using an artificial scalp. The effect of these artificial hair or scalp models did affect the measured angular acceleration. The fixation of the helmet on the head is important and needs to be controlled. Most helmets today are using a head restraint system that can be adjusted by a screw or air pump systems. The amount of adjustment must be defined in a test standard.

It can be concluded that the influence of the neck and the body on the head accelerations needs to be investigated further. Also the fixation of the helmet to the head needs to be specified.

D. IMPACT LOCATION ON THE HELMET

The impact location on the helmet should if possible be chosen from accident statistics like COST 327, McIntosh et al.1998. The impact location could either be defined with impact point or a region/area. There are benefits of defining just an impact point on the helmet as well as defining a region on the helmet. It is of course appreciated of the test engineer in the test institute can define a spot within a defined area on the helmet, as he or she will have the skill to locate the weakest point on the helmet. The limitation with defining a point on the helmet could make the helmet perform well for just that point. Defining a region on the other hand can, if the region is too large, result in a large variation in the measured angular acceleration depending on which point is chosen within the region. Fig. 3 shows an example where a HIII head equipped with an FE model of a motorcycle helmet is impacted in the front region. The helmet initial position is altered 10 degrees from a baseline position. The computed angular acceleration in this case differed around 15%.

E. PASS/FAIL CRITERIA

It is important to decide if the helmet should protect for concussion or more severe brain injuries like DAI and SDH. Current helmets are, through energy absorbing liners, optimised to reduce the linear acceleration of the head and related injuries, such as skull fractures. A study by Mertz et al (1997) estimated a 5% risk of skull fractures for a peak acceleration of 180 gravities (g) and a 40% risk of fractures for 250 g. Since rotational motion is not included in any current helmet testing standard, it is not known to what extent the current helmets reduce the rotational accelerations during a head impact. The bulk modulus of brain tissue is roughly 10^5 times larger than the shear modulus (McElhaney et al. (1976). Thus, the brain tissue can be considered as a fluid in the sense that its primary mode of deformation is shear. Therefore, rotational kinematics based injury criteria may be a better indicator of traumatic brain injury risk than linear acceleration; the most common severe injuries such as subdural haemorrhage and diffuse axonal injury are more easily caused by rotational head motion (Gennarelli et al., 1972, 1987). Similar considerations need to be given to the mechanisms of concussion and design of helmets to prevent concussion. No generally accepted thresholds exist for rotationally induced brain injuries, but the tolerance curves for diffuse axonal injury by Margulies and Thibault indicate benchmark thresholds of around 8 krad/s2 and 70 rad/s. Patton et al. (2012) suggested rotational kinematics above 4500 rad/s2 and 33 rad/s for peak resultant angular acceleration and maximum change in resultant angular velocity, respectively, to predict concussions involving loss of consciousness lasting longer than 1 minute. These limits need to be reduced when adding the translational acceleration to the impact pulse (Kleiven, 2007; DiMasi et al., 1997). It is also likely that the thresholds will need to be different for different impact directions or include the head kinematics for all degrees of freedom of the head (Kleiven, 2003, 2006).

It is possible to use a detailed FE model to derive a test specific pass/fail criteria based on the translational and rotational components as proposed by Aare and Kleiven 2004. Another proposal by Deck et al. 2012 is to use a detailed FE model of the human head and brain as a black box and compute the stress or the strain in the brain by applying the kinematics from the specific test of interest.

CONCLUSION

Several different research groups in Europe, the US and Australia have defined the importance of complementing the current helmet test methods with an oblique impact test including a tangential force. The final solution for such a test is not jet defined. The challenges are primarily to:

1. Quantify the effect of the boundary conditions to the head in all impact situations.
2. Define simple pass/fail criteria.

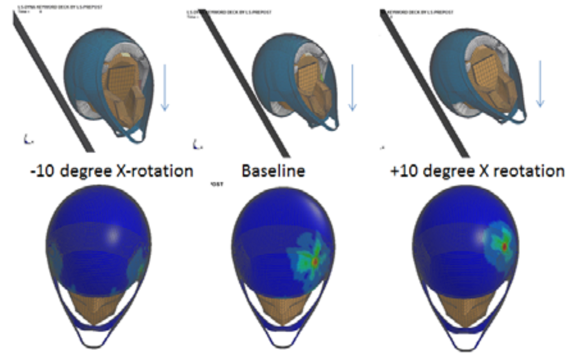

Figure 4: Example of different impact points on the helmet.

3. Design a test that is easy to use, cheap and robust.

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CONFLICT OF INTEREST

Peter Halldin is working part time for MIPS AB, a Swedish company in the helmet industry.

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