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A comparison between vinyl nitrile foam and new air chamber technology on attenuating impact energy for ice hockey helmets

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Abstract. Head injuries incurred while playing ice hockey result from a range of impact energies. The objective of this study was to compare the impact energy attenuation range of conventional multi-impact materials incorporated in ice hockey helmets to a new multi-impact technology, referred to as a 'chamber'. Three densities of 2.6 cm thick vinyl nitrile foam and two hardness values of the chamber were impacted at three drop heights and three drop masses using a free drop rig. The drop masses were chosen to represent the head mass of a young child up to an adult in order to show the level of protection provided for different head masses. Three PCB 203B force sensors collected force data at 20 kHz directly above the y axis of the impact and acceleration was calculated from the force values. Analysis revealed significant differences in peak linear acceleration between the vinyl nitrile and the dynamic air chambers ($p<0.001$). The chambers performed better throughout more impact conditions than the foam.

Keywords: linear acceleration, helmet, vinyl nitrile, chamber, energy attenuation

1. Introduction

Head injuries incurred while playing ice hockey result from a wide range of impact velocities, from a 10 meter per second (m/s) body check to a 40 m/s puck shot (Honey, 1997). This combination of high speeds, physical contact, and rigid objects make ice hockey a high-risk sport for concussion (Delaney, 2004). Helmets have inevitably become an essential element of the game helping protect the skull and brain from potential trauma. One challenge for helmet manufacturers however, is being able to protect the brain throughout the range of energies that players are being injured.

Nearly all helmets are designed to pass specific testing standards that govern safety performance requirements. Such standards implement a quantifiable pass/fail criteria, often based on peak linear acceleration (g), where acceleration is measured from a simulated helmeted head impact used to define injury thresholds (Goldsmith & Plunkett, 2004). Mass (m) and inbound velocity (v) contribute to the total impact energy (Energy = $\frac{1}{2}mv^2$) and are parameters that should be defined by helmet testing standards. The ASTM (F1045-06) standard for ice hockey helmets for example, require helmets to pass a 300 peak acceleration (g) threshold from just one impact velocity of 4.5 ± 0.09 m/s using either a 3.1, 4.1, 4.7, or 5.6 kg headform mass. Helmets are protective devises composed of an outer shell, inner liner, comfort padding/foam, and a chin strap (Liu, Chang, Chin-Ming et al., 2003). They manage the severity of a head impact by limiting the shock transmitted through the helmet to the head, which is primarily accomplished by crushing the soft material (liner) incorporated inside the helmet (Becker, 1998; Mills & Gilchrist, 2003). Helmets which are designed to pass one inbound velocity may jeopardize a player's safety, since materials incorporated in helmet liners function within a limited energy range (Avalle et al, 2001).

A five kilogram headform mass impacted at 4.5 m/s would result in an impact energy of 50.6 Joules (J). It has been stated that helmet standards which involve high-energy impacts of 40-60 J to prevent cranial fractures and severe concussions are not designed to ensure the same degree of protection at low- and medium-energy impacts (Hoshizaki, 1995). The goal of a helmet should not be to simply pass the certification standards, but rather to protect the player throughout the widest range of injurious impact conditions possible.

As mentioned, conventional polymeric materials incorporated in helmets function within a prescribed energy range. For example, if the liner density of a helmet is too soft for a given impact energy the liner would compress too quickly and bottom-out; whereas, if the liner density is too hard for a given impact the liner would fail to compress and mitigate impact energy (Avalle et al., 2001). To develop a helmet to pass the standards, two important elements are usually manipulated; first, material density and secondly, material thickness. Increasing the thickness of the liner would increase the ability of the material to attenuate energy. Helmet liners however, can only be so thick before imposing further detrimental risks, such as increased angular accelerations, decreased aerodynamic performance, and decreased aesthetic appeal (Landro et al., 2002). Once the acceptable offset distance (thickness) is prescribed, the optimal density can be defined in conventional polymeric materials for a given amount of energy to be absorbed. This makes it relatively easy for a helmet to pass a standard that employs a narrow energy range.

The ultimate goal of helmets is to mitigate the risk of head injuries and improve the level of safety during play. The purpose of this study was to compare the energy attenuation abilities of a industry standard multi-impact material incorporated in ice hockey helmets to a new multi-impact technology, referred to as a thin walled collapsible air chamber or 'chamber'. Three impact masses and three drop heights were used to compare the performance range of each material by analyzing peak linear accelerations and observing the characteristics of an acceleration time curve. It was hypothesized that there would be significance differences for peak linear accelerations between the chambers and vinyl nitrile foam samples across each impact mass and drop height. As well, it was hypothesized that there would be significant differences in energy attenuation performance between the chambers and vinyl nitrile foam samples across impact energies. The energy attenuation performance was judged by observing the yield point, functional phase, and inflections of acceleration-time curves.

2. Materials and Methods

2.1. Sample Preparation

Three densities of 2.6 centimeter (cm) thick cell-flex vinyl nitrile (VN) foam and two types of dynamic air chambers were impacted at nine different impact energies using a free drop impact system. The three densities of VN were 97, 111, and 127 kg/m3, which are referred to as VN 602, VN 600, and VN 740 respectively. These densities were chosen to represent what is commonly being used in the helmet industry. A hole saw with a diameter of 5.0 cm was used to cut all VN samples. The diameter and thickness of the samples modeled the dimensions of the chambers, which were verified using a digital micrometer. The average thickness and standard deviation for each material was 2.57 ± 0.046 cm. The density of VN was quantified using density = mass/volume (d =m/V) and weighed using a Denver Instruments SI603 scale (Gillette, Neidig, & Spencer, 1999). For each measurement, three trials were averaged and the average mass was converted into kilograms and the average volume was converted into cubic meters.

Thermoplastic polyurethane (TPU) chambers were tested in 90A and 45D durometers. The chambers have a 5.2 cm diameter and are 2.6 cm high with an interior air volume of approximately 55.2 cm^3. All chambers used in this study had a wall thickness of 2.0 mm and were vented using 2.5 mm muscle biopsy punches. The vent holes were centrally located at the bottom of the chamber. The wall thickness and vent diameter of the chambers can be manipulated depending on the application; however, for the purpose of this study these variables were kept constant. A durometer with shore values A and D were used to verify the chamber stiffness. A frontal and top view of the chamber is shown in figure 1.

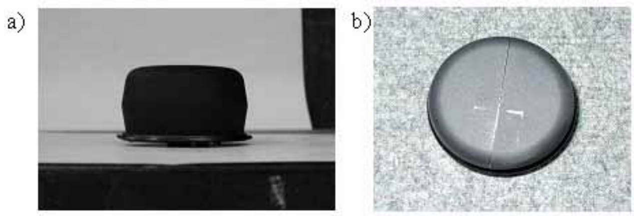

Fig. 1 The thin walled collapsible air chamber in a) frontal view and, b) top view.

2.2. Test Apparatus: Free Drop Rig

All testing was conducted using the "free drop rig", an apparatus designed for dynamic impact testing at the University of Ottawa in Canada. The free drop rig consisted of a metal cage and drop carriage (figure 2), impactor (figure 3), and a force plate anvil (figure 4). The metal cage consisted of four guide rails that supported a drop carriage, which was attached using four wheel clamps. A 12 volt ATV Winch and an ATV wire was used to elevate the drop carriage inside the metal cage to the desired dropping height by means of an Industrial Magnetics electromagnet. The impactor rested inside the drop carriage on three claws and was completely free to rebound upon impact when the drop carriage was released.

At the base of the free drop rig was a 0.2 meter (m) high by 0.61 m wide concrete block with a 3 force ring sensor anvil directly under the centre of the drop carriage. For the chamber samples, a sold metal jig with air channels was placed on top of the force sensor anvil to allow air to escape the chambers during impact. This jig was removed for testing the vinyl nitrile samples. The concrete block was installed to help prevent ground noise which could interfere with the force ring signal.

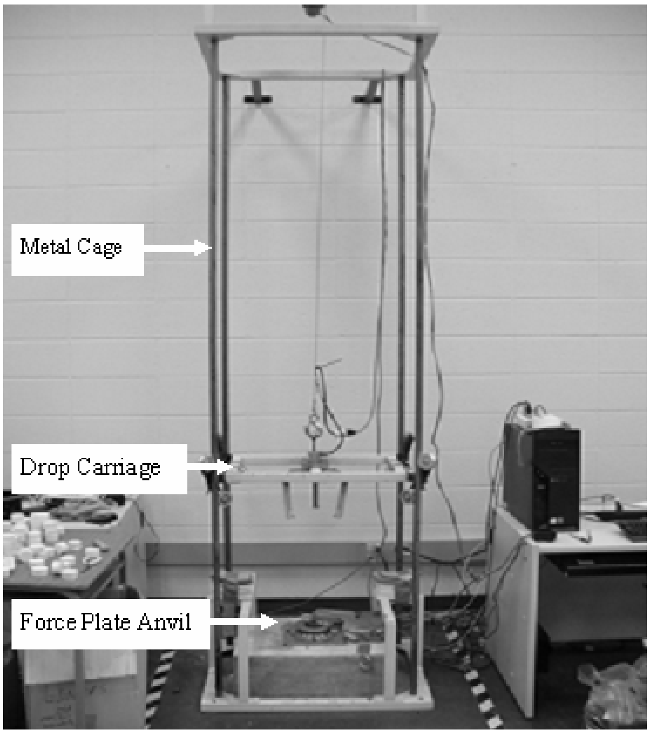

Fig. 2 The free drop rig developed at the University of Ottawa for material testing.

The impactor consisted of a steel cylinder of 12.2 cm high by 13.8 cm in diameter with a lip at the top for attachment to the drop carriage. The impactor itself weighed 2.0 kg without the added one kilogram calibrated cylindrical weights, which were positioned incrementally over the center of gravity of the impactor to give 3.04, 4.04, and 5.04 kg. The sensors used for the force recordings were three PCB model 208C05 piezoelectric uniaxial force rings, with a model 482M66 summing signal conditioner. The signal conditioner was attached to an analog-to-digital board (National Instruments) by BNC and the signal was then fed through to the computer by way of a PCI 6221 NIDAQ card (National Instruments). The force recordings were collected at 20 kHz to ensure enough information was acquired per impact, and then stored on computer. Further analysis of the force recordings was performed using the Bioproc 2 program developed by Dr. D.G.E. Robertson at the University of Ottawa (Robertson, 2007). The force sensor was calibrated against a Kistler 9281B piezoelectric force plate.

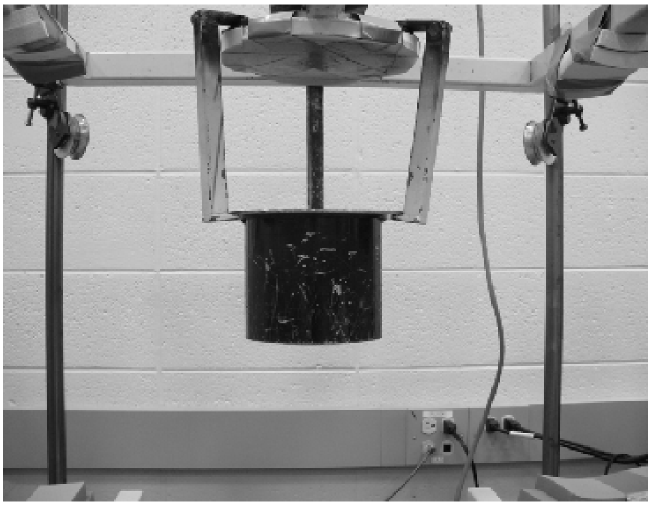

Fig. 3 The impactor resting freely on the three claws inside the drop carriage of the free drop rig.

2.3. Research Protocol

An observational, fully crossed design was used for all data collection. There was no effect on the order of treatments; therefore, it was not necessary to randomize trials as each impact condition was completely independent from the other. All testing was conducted in ambient conditions. Prior to testing, the samples were examined and the results were recorded to minimize any variation in the foam and chamber production. A single sample was positioned in the center of the testing jig for each set of trials. An Industrial Magnetics electromagnet was used to raise the impactor to the desired heights of 20, 40, and 60 cm. These drop heights were chosen to capture the energy range at which the samples were able to perform efficiency. Turning the power off released the electromagnet cleanly from the drop carriage to ensure a flat impact.

Each sample was impacted five times at each drop height using each impact mass. Three sets were conducted in total, resulting in a total of 135 impacts per material type: 9 conditions by 5 impacts by 3 sets. The three impact masses of 3.04, 4.04, and 5.04 kg were used to represent the head mass of a young child up to an adult in order to show the level of protection provided for different head masses. The impact energy of each test is presented in table one below.

Tab. 1 The impact energy (J) for each drop height and impact mass.

	Drop Height (Inbound velocity)		
	20 cm (1.9 m/s)	**40 cm (2.8 m/s)**	**60 cm (3.4 m/s)**
3.0 kg	5.9 J	11.8 J	17.7 J
4.0 kg	7.8 J	15.7 J	23.5 J
5.0 kg	9.8 J	19.6 J	29.4 J

3. Results

A three-way Analysis of Variance revealed significant peak linear acceleration differences between material type, impact mass, and drop height ($p<0.001$). The mean acceleration and standard deviation measurements are shown in the table below.

The effect size, which displays the strength of the relationship that each variable had on predicting peak linear accelerations were 52.4% for material type, 50.7% for impact mass, and 88.9% for drop height. As well, significant two-way interactions were found between impact mass and drop height, material and drop height, and material and impact mass indicating inconsistency in the interaction between one variable throughout the different levels of the second variable. The drop height is the primary cause for the interaction effects. For example, as impact mass increased the peak linear accelerations decreased for all TPU 45D chambers at each drop height except 60 cm. At 60 cm, the TPU 45D chambers were not able to manage the bulk of the impact energy and failed or bottomed-out, resulting in unpredictable energy attenuation characteristics.

Tab. 2 Mean peak linear acceleration and standard deviation (SD) for TPU 45D, TPU 90A, VN 602, VN 600, and VN 740 for all impact conditions, where n = 5 and N = 675.

		Peak Linear Acceleration (g)					
		20 cm	**SD**	**40 cm**	**SD**	**60 cm**	**SD**
TPU 45D	3.04 kg	41.8	1.3	44.3	2.1	48.2	18.5
	4.04 kg	30.8	1.2	31.5	2.3	47.6*	9.4
	5.04 kg	24.9	1.6	28.2	1.4	115.2*	28.2
TPU 90A	3.04 kg	29.6	1.4	30.4	2.0	47.7*	8.5
	4.04 kg	22.0	1.6	29.4	2.9	151.7*	20.4
	5.04 kg	17.2	1.2	61.8	15.2	201.9*	29.8
VN 602	3.04 kg	19.9	1.0	47.1*	4.2	107.3*	14.3
	4.04 kg	20.6	1.7	66.5*	8.6	153.8*	16.0
	5.04 kg	25.8*	3.5	78.6*	11.3	204.9*	29.3
VN 600	3.04 kg	22.3	1.7	43.5*	5.5	82.6*	12.1
	4.04 kg	21.0	1.9	53.8*	8.4	117.2*	19.8
	5.04 kg	22.3	2.7	65.2*	12.6	175.0*	42.1
VN 740	3.04 kg	36.6	5.1	39.7	5.1	54.3*	4.9
	4.04 kg	28.1	3.7	42.1*	9.9	67.8*	13.1
	5.04 kg	22.4	2.4	42.1*	6.3	81.0*	20.5

* Indicates a sharp inflection in the acceleration-time curve (material failure).

Post hoc analysis using the Bonferonni test revealed significant differences between all chambers and foam except VN 740 and TPU 45D, as well as VN 600 and TPU 90A. VN 740 was the highest density of the VN samples, and the TPU 45D was the harder of the two chamber durometers tested. A similar relationship existed between VN 600 and TPU 90A, which were the softer samples and therefore had closer attenuation characteristics. Pos hoc analysis confirmed significant differences across each impact mass and drop height. Figure six displays acceleration-time graphs, comparing TPU 45D and VN 600.

In figure six, the drop height increases from left to right and the impact mass increases from top to bottom, displaying the nine impact conditions tested. Three characteristic features observed from these curves include the yield point, the functional phase, and the sharp inflections. The yield point or breaking point is the position at which the curves began to flatten or level-out. This was found at the end of the initial slope of the curve, which is known as the linear elastic phase or young’s modulus (Landro et al., 2001). The chambers were designed to first resist an impact using the material and wall stiffness. They were then engineered to manage the remainder of the energy through air venting. This allowed the chamber to succumb to significantly greater accelerations before compressing, which explained the higher yield points for TPU 45D.

The plateau or functional phase occurred when the air cells collapsed and absorbed the bulk of the impact energy. A flatter force curve indicates higher energy absorption efficiency (Yu-Hallada, Kuczynski, & Weierstall, 1998). The functional phase was a better indicator than peak linear acceleration at displaying the performance capabilities of the samples. The unfavorable sharp inflection in the acceleration-time curves resulted when the air cells collapsed and the cell walls came in contact. Material densification causes the stress to increase steeply (Avalle et al., 2001; Landro et al., 2002; Viot et al., 2005). An ideal energy absorber is able to manage the impact over a longer period of time, helping reduce the peak spike of energy (Heh & Stadnik, 1997). Figure six revealed that the vinyl nitrile foam began bottoming-out at around 20 cm using a 3.0 kg impact mass, opposed to TPU 45D which did not start bottoming-out until the higher impact energy at 60 cm using a 5.0 kg impact mass. Independent of peak linear acceleration values, it was concluded that the TPU 45D chamber had better energy attenuation performance.

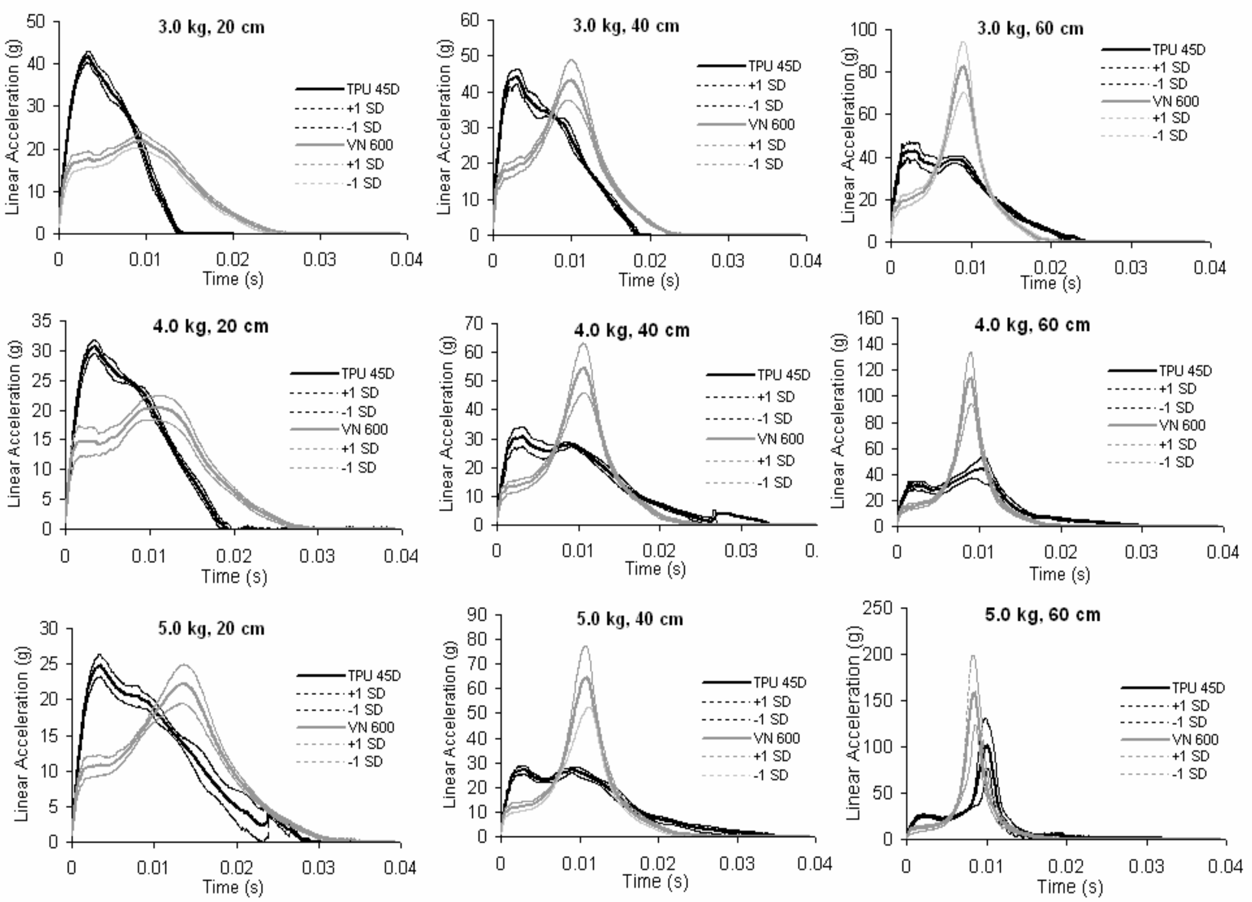

Fig. 6 Linear acceleration time trace graphs for TPU 45D and VN 600 20, 40, and 60 cm using a 3.0, 4.0, and 5.0 kg impact mass.

The following figure shows the results for all samples tested at 40 cm using a 4.0 kg impact mass. The chambers were able to manage the energy throughout the entire duration of the impact, without the distinctive acceleration spike found for VN 600, VN 602, and VN 740.

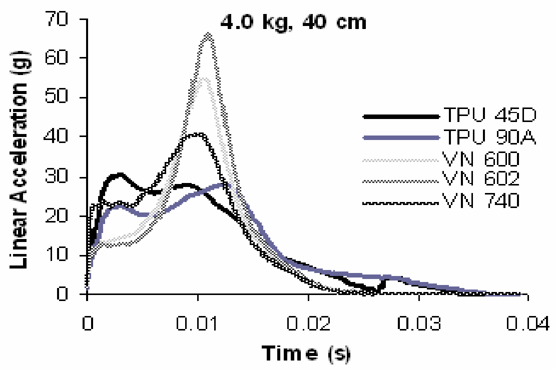

Fig. 7 Linear acceleration time curves for TPU 45D, TPU 90A, VN 600, VN 602, and VN 740 when impacted at 40 cm using a 4.0 kg impact mass.

4. Discussion

The data showed that the chambers were able to better manage the impact energy throughout a wider range of drop heights and impact masses. This was indicated by observing the functional range of each material upon impact. The hypotheses that significance differences for peak linear accelerations and energy attenuation performance would be found between the chambers and vinyl nitrile foam across each impact mass and drop height were supported. The chambers were able to adapt to the impact energy more effectively than VN, providing a more optimized response throughout the variety of impact energies tested.

The chambers in general, have the potential to absorb more energy than current helmet technology. There are four main engineering parameters which can influence how the chambers absorb energy: material type, wall thickness, vent diameter, and the dimensions of the chamber. In this study, only two durometers of TPU were tested; however, there is potential to use other durometers. As well, the wall thickness, the vent diameter, and the dimensions of the chamber were kept constant; however, they can be adjusted to match the energy demands of the intended application.

The dimensions of the material samples are important considerations during dynamic impact testing. It has been shown that the compressive properties of open cell foams vary as the cross-sectional area changes in size relative to the indenter. Material samples with cross sectional areas smaller than the indenter, such as in this study, exhibit lower stiffness characteristics compared to samples larger than the indenter. When the sample is larger than the indenter it is suggested that the shear forces created during compression between the material and the sides of the indenter is included in the total stress calculations (Todd et al., 1998). It has therefore been recommended that researchers choose the size of their testing material similar to the intended application. For this study, the indenter was larger than the samples, to help limit the effect of shear forces between the two.

Overall, drop height had the strongest effect size on peak linear acceleration (88.9%) compared to impact mass and material type. Considering athletes are injured throughout a range of inbound velocities (which correlates to dropping height); it is presumed that the helmet standards which use one inbound velocity are putting players at a greater risk of head trauma. A helmet does not perform optimally when a player impacts their head outside of the certification energy range (Hoshizaki, 1995). Since foams are designed to function within a narrow range of energy, it is vital that we develop new technology to better protect our athletes. The chambers, as shown in this study, have the engineering potential to effectively manage a greater range of impact energies compared to VN foam.

For the purpose of this study all materials were tested separate from a helmet. A future study using a full helmet with multiple chambers would provide further insight into energy attenuation performance of the venting air chambers.

5. Conclusion

Overall, the chambers attenuated energy more effectively throughout a wider range than vinyl nitrile. Drop height (88.9%) was more influential than impact mass (50.7%) on predicting peak linear acceleration. Replacing foam with a new technology may be the answer to increasing the energy range at which helmets are able to manage impact forces and reduce the risk of brain injury.

6. Acknowledgements

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