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Optimisation of energy absorbing liner for equestrian helmets

Part I: Layered foam liner

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ABSTRACT

The energy absorbing foam liner used in safety helmets was optimized using finite element modelling. Computational simulations of certification standard tests were carried out to obtain the best performing configurations of helmet liner. For each test condition, the best configuration of helmet liner was identified. Two alternative designs were considered: the first was composed of three layers of different foam density, the second was a conventional liner of one single uniform density. The observed reduction in peak acceleration for the best performing helmet liners in various test conditions are directly related to the contact area, the distribution of material stresses and the dissipated plastic energy density (DPED). Peak linear accelerations are shown to be lowered by increasing the contact areas of the inner and outer surfaces of the energy absorbing liner, or by varying the foam density through the thickness of the liner to ensure that the foam absorbs energy plastically when the stress reaches the late plateau stage of the foam stress-strain curve.

KEYWORDS:

Safety helmets, layered foam liner, Head impact

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INTRODUCTION

Epidemiological studies have shown that horse racing is a particularly risky sport [1-11]. Compared to other racing athletes, the race jockey is at a higher risk of suffering injury [3, 12-14]. Paix [14] reported an overall injury incidence of 0.88% per competitor per event for equestrian racing, which exceeds those reported by Chapman and Oni [15] of 0.24% for motorcycle racers and 0.14% for car racers. The main cause of injury for jockeys was found to occur from being thrown off the horse. Reasons for the incidence and severity of injuries in equestrian sport include the particular rider position (not seated, gripping the horse with lower legs, back parallel to horse's back), the height of the jockey above the ground (around 3 meters), and the unpredictability, power, speed, and mass of the horse. There is also a high risk of being kicked or trampled by another horse after a fall. The study by Whitlock [16] showed that most of the injuries sustained by jockeys were to the head/face (31%) and most (83%) hospitalized jockeys suffered head injury, whereas Waller [17] showed that head injuries represented 17.7% of injuries caused by being thrown off a horse, and head/neck/face injuries represented 18.8% of all injuries. The correct usage of a helmet can efficiently protect the head and reduce the severity of head injury arising from a head impact event. The effectiveness of helmets in leisure riding has been shown [5-8, 18-21] through the reduced incidence of serious head injury among those groups wearing helmets.

Much recent work has been published on the design and safety aspects of motorcycle and bicycle helmets [22-28] and on helmets used in other sports [29-33]. However, literature that relates to equestrian helmets is relatively old and limited in technical scope [34-36]. The present paper aims to address this deficit by examining the energy absorbing liner of equestrian helmets in light of advances in materials technology and the performance requirements of the tests of certification standards.

EN 1384:1996 [37] is the current European standard being used to certify equestrian helmets for both leisure and race riding. This standard has helped to improve the performance of equestrian helmets and it has been shown that the introduction of this standard has contributed to reducing head injury [34]. Nevertheless, there are situations where equestrian helmets could be improved. The more recent high performing helmet standard EN 14572:2005 [38] is intended for helmets for "high-risk" activities, but it does not supersede EN 1384:1996. The EN1384:1996 standard describes an impact speed of 5.4 m/s, while the new standard EN 14572:2005 specifies a "high energy" impact velocity (7.7 m/s), as well as a "low energy" impact velocity (4.4 m/s). For a helmet to pass standard EN 1384:1996, the headform acceleration during this standard impact shall not exceed 250 g (g=9.81 m/s^2) at any time, and the total time for which it exceeds 150 g shall not be greater than 5 ms. As specified in standard EN 14572:2005, it should conform to the same criterion but with an impact velocity of 7.7 m/s. Moreover, when tested at the low impact velocity of 4.4 m/s, the acceleration shall not exceed 80 g at any time. The intention of introducing these two new levels of impact energy was intended to represent situations where impact speeds are higher, such as in the case of horse kicks or falls at high speed, and simultaneously to protect against low energy impacts, where a conventional (1384) helmet would not absorb energy. EN 14572:2005 claims that conforming helmets offer higher protection against side impacts; however, at present no commercially available helmet conforms to this standard. The EN14572:2005 standard also includes impact tests against hazard and hemispherical anvils (tested at 6.3 m/s impact speed). A particular challenge in manufacturing helmets to pass this standard is the requirement for a helmet to simultaneously protect against both high and low energy impacts. The current study aims to suggest a possible solution to manufacturing helmets conforming to standard EN14572:2005 by optimising the liner density. In this paper, a layered foam liner is proposed to improve the energy absorption performance. The advantage of the layered foam liner is that it can be manufactured with with current techniques; however, the disadvantage is that stresses can be localised at the interfaces between layers due to the discrete change in material properties, which could lead to delamination and crack propagation at these interfaces unless particular care is taken during manufacturing. A companion Part II paper to this present paper describes a continuous gradient in the foam liner which avoids these disadvantages.

A generic finite element (FE) helmet model and the materials for the components of the helmet are introduced in the following section. The test conditions and helmet liner configurations for the simulations are then described. The best performing design configurations for one impact position are considered in detail. The peak acceleration, the contact areas at the inner and outer surfaces of liners, the von Mises stress and the dissipated plastic energy density in various layers are analysed in detail. The relationship between the peak acceleration, the contact area, the stresses, and the plastic energy is illustrated finally.

DESCRIPTION OF HELMET MODEL

Virtual numerical helmet models have been developed for various applications including motorcycle helmet [23, 24, 39, 40], bicycle helmet [28] and ballistic helmet [41, 42]. Little effort has been made to model equestrian helmets. The current study developed a FE model of an equestrian helmet based on the geometry of common helmets that are readily available in the European market. The helmet model consists of an outer shell, a foam liner, a foam block and a ring, as shown in Fig. 1. The headform is simulated as a rigid body with no consideration given to headform deformation and energy absorbed by the headform. This is considered to be a good approximation, as the headform in the certification standards is made of aluminium, which has a much higher stiffness than the helmet components. The standard test headforms do not consider head deformation and energy absorbed by the head. Only a flat rigid anvil is considered in these current simulations and no impacts against either hazard or hemispherical anvils have been considered. While these simplifying assumptions may limit the present results, the objective of the current study has been to suggest ways of improving the energy absorption capacity of helmet liners by varying the density (and hence the mechanical characteristics) of liner foam. Other aspects such as liner thickness, shell stiffness, and helmet geometry will be considered subsequently.

Fig. 1

In the helmet model, the outer shell is modelled as linear elastic material and the ring is modelled as a rubber elastomer with Poisson's ratio approaching 0.5 (almost incompressible). The foam block between the shell and foam liner is modelled as a hyperelastic elastomeric compressible foam with material constants specified by experimental test data [43]. The purpose of the foam block is to bond the shell and liner together, and also to leave a small gap between the shell and liner to allow the shell to deform and absorb some energy before the foam liner crushes in an impact.

The foam liner material used in commercially available equestrian helmets is typically expanded polystyrene (EPS) foam. EPS foam is popularly used in energy absorbing structures, e.g. [44, 45]. The foam liner is modelled in ABAQUS/Explicit using the crushable foam model with a volumetric hardening rule in conjunction with the linear elastic model [46]. The hardening behaviour for the polymeric foam is defined by the constitutive stress-strain relationship. The stress-strain curve for the polymeric foam is a function of foam density. Constants for the constitutive model used in the current study have been tested and determined in a previous study by the authors [47]. Stress-strain curves for foams of any densities used in the present simulations can be obtained from the constitutive model [47]. Representative curves are illustrated in Fig.

2. Recognising that cellular foams can be strain rate sensitive [48], such rate sensitivity will be incorporated into a future constitutive model.

The constitutive relationship for EPS foam is tri-linear in form, corresponding to elastic, plateau, and densification stages. It is more efficient that the foam liner absorbs energy within the plateau stage as the stress remains nearly constant over a large strain. This efficiency is defined [49, 50] as the ratio of the absorbed energy up to the stress, σ, to the stress itself. The efficiency increases from the elastic stage until the end of the plateau stages. Table 1 shows the calculated yield stresses along with the range of plateau stresses for typical densities used in the present simulations.

Fig. 2

ABAQUS/Explicit [43] with a central-difference time integration rule was used for the finite element helmet dynamic impact tests. The headform was modelled using a three dimensional four node elements (R3D4) with a rigid body constraint at the centre of mass, from where the linear headform accelerations were read. The liner and foam block were modelled as three dimensional eight node linear brick elements with reduced integration and hourglass control (R3D8R). The shell was modelled with four node doubly curved thin shell, reduced integration, hourglass control, finite membrane strain model elements (S4R) with a section thickness of 2mm. The maximum stable time increment was calculated by

$$\Delta t \approx \frac{L_{\min}}{C_d}$$

where $L_{\min}$ was the smallest element dimension in the mesh and C_d was the wave propagation speed. The stable time step was chosen and updated automatically by ABAQUS throughout the solution.

A mesh sensitivity analysis was conducted to observe the effect of mesh density on the simulation results, to determine the most efficient mesh density. Different impact orientations and three different mesh densities were used, while maintaining a similar aspect ratio for all elements. The three liner models in these meshes had 3, 6, and 9 elements through their thickness and the total number of elements in a model was increased throughout the element liner mesh to keep all element aspect ratios close to 1. Simulations were run assigning uniform and layered crushable foam properties.

For impact positions other than the crown impact, for the different density mesh liners used, it was observed that the results for dissipated plastic energy, angular acceleration, and linear acceleration were within a small range (Table 2 shows results for a frontal 45° incline impact). The artificial energy (energy associated with constraints used to remove singular modes, such as hourglass control, during finite element modelling [43]) generated by the model decreased considerably as the liner mesh density was increased, but even for the lower density mesh the artificial energy was a small portion of the total dissipated plastic energy and the acceleration values obtained were very similar to those obtained from higher density meshes. Also, since computation time was an important factor to consider when conducting the large number of simulations, it was evident that even when using the lower mesh density models (faster simulation times) the results obtained were adequately accurate, as the time history behaviour of the desired output variables matched and their magnitudes were very similar.

For the crown impact position, results were similar for low and medium impact speed levels (4.4 and 5.4 m/s), but the model had considerable variability depending on mesh density for the crown impact at high impact speed (7.7 m/s). Table 2 shows the significant change in vertical linear acceleration when liner mesh density was changed. The mesh density of the hyperelastic foam block between the shell and the liner was seen to have the largest effect. Impacts near the crown area were seen to be sensitive to the mesh density of the foam block. After simulating the crown high speed impact at different mesh densities for helmet liner and foam block, a liner model having 6 elements through the thickness and a higher mesh density foam block with 6 elements across the thickness as opposed to 3 elements across the thickness was chosen for subsequent high speed crown impact simulations. This gave satisfactorily accurate results in a reasonable simulation time.

SIMULATION PARAMETERS

The mechanical parameters of the helmet materials used in the simulations are listed in Table 3. To evaluate the energy absorption performance of the helmet with various liner density configurations, impact simulations were performed with three impact positions as listed in Table 4 and three impact velocities as suggested in standards EN1384:1996 and EN 14572:2005. The impact velocity of 5.4 m/s is referred to as the “1384 impact”, the impact velocity of 4.4 m/s is referred to as the “low energy impact” and the impact velocity of 7.7 m/s is referred to as the “high energy impact”. Typical test configurations are illustrated in Fig. 3. The foam liner material used in commercially available equestrian helmets is typically EPS foam of density 64 kg/m^3. To optimise the liner density in this present investigation, densities that were different from this actual density were tested, and used to define liners with layered densities for the aforementioned impact positions and impact velocities, as shown in Tables 4 and 5. The uniform densities of 64 kg/m^3 and 50 kg/m^3, and the layered densities 50-25-25 kg/m^3 and 80-64-64 kg/m^3 are tested for all impact positions and all impact velocities, as it was these configurations of liner densities that displayed the best performance. The three numbers for the layered liner indicate the density of each of the three layers, from the inner to the middle to the outer layers (inner is closest to head; outer is closest to shell of helmet). The remaining densities in Table 5 are only tested for the 45^{o} side impact.

Fig. 3

SIMULATION RESULTS

Peak Accelerations

The peak accelerations of the best performing helmets with three equally thick layered foam liners are compared with those of uniform foam liners in Table 6. As there was negligible improvement for three impact positions for the high energy impact, these improvements are still insufficient to make the helmet pass standard EN 14572:2005. For all the three impact positions, helmets with layered foam liner of density 50-25-25 kg/m^3 substantially improved energy absorbing performance in the low energy impact; helmets with uniform foam liner of density 50 kg/m^3 considerably improved energy absorbing performance in the 1384 impact. However none of the considered layered foam liners performed better than the uniform foam liner for the high energy impact in the 45 ° side impact.

Contact Areas

The contact area between the inner surface of the liner and the headform, and the contact area between the outer surface of the liner and the shell are also analysed for the 45 ° side impact. Fig. 4 compares the evolution of the contact areas for the uniform liner and the layered foam liner. In the 1384 impact and the low energy impact, the contact areas in the layered foam liner remain obviously larger than in the uniform liner throughout the impact and at both the inner surface and the outer surface (Figs. 4(a), 4(b)). In the high energy impact, the contact areas at both surfaces remain slightly smaller in the layered foam liner than in the uniform liner (Fig. 4(c)). It is noteworthy to realise that the larger contact areas are consistently related to the lower peak accelerations.

Fig. 4

Distributions of Von Mises Stresses

The distribution of stress and energy absorption through the thickness of the uniform foam liner as well as through the thicknesses of the layered foam liner are analysed below for the 45^{o} side impact. This serves to explore how the layered liner improves the energy absorption beyond that provided by the uniform foam liner. The distributions of von Mises stresses at peak acceleration in the inner, middle and outer layers of the layered foam liner and the uniform foam liner are compared in Figs. 5(a) to 5(c). When generating the distribution plot, 20 equal intervals of von Mises stresses in the range of [0, 1500] kPa are considered, as shown along the x-axis. The volume fraction of liner materials in the corresponding layer exhibiting stresses in each stress interval is calculated and indicated by "○" or "□ ". The distribution plot is generated by connecting the "○" or "□ " volume fractions. To illustrate the mechanics of energy absorption more clearly, only the liner materials that contributed to the plastic energy dissipation are considered for this von Mises stress analysis. These materials are found to be localised around the impact position. Note that, to ensure a direct comparison between the uniform foam liner and the layered foam liner, both types of liner were considered to contain three layers through the thickness in the FE simulations.

Fig. 5

As shown in Fig. 5, for the uniform liner, stresses in different layers are comparable, while there are only smaller volumes of liner material reaching these levels in the outer layer than in the inner layer. The majority of the foam material in the energy absorbing liner reaches stresses between 500 kPa and 600 kPa. However, the stress levels in the layered foam liner are shifted by the density levels. The densities of the three layers in the 1384 impact are all 50 kg/m^3, and the majority of stress levels in the inner, middle and outer layers are around 450, 400, and 350 kPa, respectively (Fig. 5(a)). The densities of the inner, middle and outer layers in the low energy impact are 25 kg/m^3, 25 kg/m^3, and 50 kg/m^3, respectively, while the stress level in the inner layer (majority around 300 kPa) is higher than in the middle and outer layer (majority around 150 kPa) (Fig. 5(b)). The densities of the inner, middle and outer layers in the high energy impact are 80 kg/m^3, 64 kg/m^3, and 64 kg/m^3, respectively, while the majority of stress levels in the inner, middle and outer layers are around 775, 625, and 550 kPa, respectively (Fig. 5(c)).

By comparing the stresses in Fig. 5 and the yield stresses and plateau stresses as listed in Table 1, the relationship between the plastic energy dissipation and the foam density is illustrated more clearly. For the uniform foam liner of density 64 kg/m^3, the plateau stress ranges from 450 kPa to 970 kPa, while the majority of the foam contributing to plastic energy dissipation in all of the three impacts reaches stresses between 500 kPa to 600 kPa, which is in the initial and early plateau stage of the compression stress-strain curve of the foam. For the layered foam liner in the 1384 impact, the liner with three layers of density 50 kg/m^3 reaches the early and middle plateau stage (350-760 kPa). For the layered foam liner in the low energy impact, the outer layer of density 25 kg/m^3 reaches the middle and late plateau stage (180-380 kPa); the middle layer of density 25 kg/m^3 reaches the early and middle plateau stage;

the inner layer of density 50 kg/m^3 reaches the initial plateau stage. For the layered foam liner in the high energy impact, the inner layer of density 80 kg/m^3 reaches the initial and early plateau stage (580-1200 kPa) and the middle and outer layers of density 64 kg/m^3 also reaches the initial and early plateau stage (450-970 kPa). It is more efficient for foam to absorb energy in the late plateau stage than in the early plateau stage. Therefore, the layered foam liner in the 1384 impact (especially the inner layer) and in the low energy impact (especially the middle and outer layers) improves the energy absorption efficiency, while the layered foam liner in the high energy impact does not really improve the efficiency; at best, it is comparable to the uniform foam. These findings agree with the previous comparison of peak accelerations between the uniform foam liners and the layered foam liners (Table 6).

Dissipated Plastic Energy Density (DPED)

The comparison of the DPED (the quantity of dissipated plastic energy normalised by the corresponding volume of material) between the layered foam liner and the uniform foam liner is illustrated in Figs. 6(a) to 6(c). For all the test conditions, the DPED for all the uniform foam liners decreases from the innermost layer to the outermost layer. This is because the amount of material contributing to plastic energy dissipation decreases from the innermost layer to the outermost layer, as described above.

Fig. 6

For the layered liner in the 1384 impact, all the three layers reach the early and middle plateau stage with decreasing volumes of foam contributing to plastic energy dissipation from the inner to the outer regions (Fig. 5(a)). Therefore, the DPED of all the three layers is higher than the corresponding layer of uniform liner with the same decreasing trend from the inner to the outer layers (Fig. 6(a)). For the low energy impact, the energy density is much higher in the middle and outer layers in the layered liner (Fig. 6(b)), which is consistent with the comparison of stress levels (Fig 5(b)). Therefore, the energy density for the whole layered liner is higher than for the whole uniform liner in both the 1384 impact and the low energy impact. In the high energy impact, the inner layer of density 80 kg/m^3 exhibits the lowest energy density, and the middle layer of density 64 kg/m^3 exhibits the highest energy density (Fig. 6(c)). This is consistent with the analysis of the stress levels and the volumes of liner material contributing to plastic energy dissipation (Fig. 5 (c)).

DISCUSSION

In this paper, a finite element helmet model for a generic equestrian helmet has been developed to design and optimise energy absorbing liner materials. This model was established based on a number of simplified assumptions (i.e., simplified shell and headform material). However, it is practicable for the current optimisation design study for the helmet liner, as the helmet is an accurate representation of a typical equestrian helmet since the baseline model that was used was shown to perform satisfactorily against the EN1384 impact test. The FE simulations of standard impact tests were carried out to improve the energy absorption performance of helmets by optimising the liner density.

For each test condition, one best performing layered liner configuration was achieved. For the layered liner configuration, the average liner density was varied. The observed decreases in the peak accelerations for the best performing helmets in various test conditions are found to be related to the contact area, the distribution of internal stresses, and the DPED: the peak acceleration is reduced when the contact areas between the liner and either the inner headform or the outer shell are larger; the peak acceleration is reduced if the stress of the foam liner when absorbing the energy is in the late plateau stage or if a larger part of the liner contributes to plastic energy dissipation; the peak acceleration is reduced when the DPED in the foam liner is increased.

Plastic deformation is more extensive in the inner layers of the liner than in the outer layers around the impact position. The inner layers are crushed before the outer layers. The use of a layered liner with higher density foam on the inside would serve to strengthen the inner side of the liner and the use of a liner with lower density foam on the outside could actually improve the efficiency of material usage. The ideal optimised liner configuration would have the highest energy efficiency throughout the thickness, i.e., the foam with various densities throughout the thickness would absorb the energy at the late plateau stage for the corresponding densities.

It is possible to make a liner with different density layers with current manufacturing techniques. Many current motorcycle helmets already have different liner sections to improve energy reduction depending on the location in the helmet. Some equestrian helmet manufacturers have implemented two different foam densities in sandwich configurations, but these are still not widespread. Computer methods such as the ones illustrated in this study can help understand and justify the use of different density layers since they allow the analysis of the transient behaviour and individual performance of each layer in a much clearer manner than in experimental tests. In an actual test, only the initial and final stages are easy to analyze and the behaviour of the material cannot be assessed directly as the transient helmet performance is only seen indirectly through the headform acceleration.

CONCLUSIONS

The current FE study suggests a possible approach to manufacturing helmets that could conform to the high performance equestrian standard EN14572:2005 without increasing the overall size or weight of the helmet. This avoids increasing the inertia of a helmet, which could add to neck injuries in the event of rotational acceleration. It is also shown how FE can be used to optimise helmets by not only using headform linear accelerations, but also by using variables directly related to the helmet performance such as contact area and energy absorption. This suggests that helmets can be optimized in a more methodical manner where the influence on performance of each helmet section and/or component can be isolated and targeted more efficiently. Although the current study of helmets using optimised density foams has not provided a specific solution for a helmet which conforms to standard EN14572:2005, it does provide a way to improve the performance significantly in regards to the current EN1384:1996 standard. A future study will consider alternative ways to improve the helmet performance, such as by increasing the thickness of a liner, or the performance of the outer shell of a helmet.

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REFERENCES:

[1] Balendra G, Turner M, McCrory P, Halley W. Injuries in amateur horse racing (point to point racing) in Great Britain and Ireland during 1993-2006. Br J Sports Med 2007;41:162-6.

[2] Turner M, McCrory P, Halley W. Injuries in professional horse racing in Great Britain and the Republic of Ireland during 1992-2000. Br J Sports Med 2002;36:403-9.

[3] McIntosh AS, McCrory P. Preventing head and neck injury. Br J Sports Med 2005;39:314-8.

[4] Chitnavis JP, Gibbons CLMH, Hirigoyen M, Parry JL, Simpson AHRW. Accidents with horses: What has changed in 20 years? Injury 1996;27(2):103-5.

[5] Abu-Zidan FM, Rao S. Factors affecting the severity of horse-related injuries. Injury 2003;34(12):897-900.

[6] Holland AJA, Roy GT, Goh V, Ross FI, Keneally JP, Cass DT. Horse-Related injuries in children. Med. J. of Australia 2001;175:609-12.

[7] Northey G. Equestrian Injuries in New Zealand, 1993-2001: Knowledge and experience. The New Zealand Medical Journal 2003;116(1182):1-8.

[8] Petridou E, Kedikoglou S, Belechri M, Ntouvelis E, Dessypris N, Trichopoulos D. The mosaic of equestrian-related injuries in Greece. The Journal of Trauma, Injury, Infection and Critical Care 2002;56(3):643-7.

[9] Gabbe BJ, Finch CF, Cameron PA, Williamson OD. Incidence of serious injury and death during sport and recreation activities in Victoria, Australia. Br J Sports Med 2005;39:573-7.

[10] Griffen M, Boulanger BR, Kearney PA, Tsuei B, Ochoa J. Injury during contact with horses: recent esperience with 75 patients at a level I trauma center. South Med J 2002;95(4):441-5.

[11] Yima VWT, Yeunga JHH, Maka PSK, Grahama CA, Laib PBS, Rainer TH. Five year analysis of Jockey Club horse-related injuries presenting to a trauma centre in Hong Kong. Injury 2007;38(1):98-103.

[12] Cripps RA. Horse-related injury in Australia. Australian Injury Prevention Bulletin; 2000.

[13] D'Abreu F. Brain damage in jockeys. Lancet 1976;307(7971):1241.

[14] Paix BR. Rider injury rates and emergency medical services at equestrian events. Br J Sports Med 1999;33:46-8.

[15] Chapman MAS, Oni J. Motor racing accidents at Brands Hatch, 1988/9. Br J Sports Med 1991;25:121-3.

[16] Whitlock MR. Injuries to riders in the cross country phase of eventing: The importance of protective equipment. Br J Sports Med 1999;33:212-4.

[17] Waller AE, Daniels JE, Weaver NL, Robinson P. Jockey Injuries in the United States. J Amer Med Assoc 2000;283:1326-8.

[18] Fleming PRI, Crompton JL, Simpson DA. Neuro-ophtalmological sequelae of horse-related accidents. Clincal and Experimental Ophathalmology 2001;29:208-12.

[19] Ingemarson H, Grevsten S, Thoren L. Lethal horse-riding injuries. J Trauma 1989;29(1):25-30.

[20] Lim J, Puttaswamy V, Gizzi M, Christie L, Croker W, Crowe P. Pattern of equestrian injuries presenting to a Sydney teaching hospital. ANZ J Surg 2003;73:567-71.

[21] Bond GR, Christoph RA, Rodgers BM. Pedatric equestrian injuries: Assessing the impact of helmet use. Pediatrics 1995;95(4):487-9.

[22] Aiello M, Galvanetto U, Iannucci L. Numerical simulations of motorcycle helmet impact tests. Int J Crashworthiness 2007;12(1):1-7.

[23] Cernicchi A, Galvanetto U, Iannucci L. Virtual modelling of motorcycle safety helmets: Practical problems. 6th European LS-DYNA Users's Conference,

Gothenburg, Sweden: 2007; 2007.

[24] Shuaeib FM, Hamouda AMS, Wong SV, Umar RSR, Ahmed MMHM. A new motorcycle helmet liner material: The finite element simulation and design of experiment optimization. Materials & Design 2007;28:182-95.

[25] Kostopoulos V, Markopoulos YP, Giannopoulos G, Vlachos DE. Finite element analysis of impact damage response of composite motorcycle safety helmets. Composites: Part B 2002;33:99-107.

[26] Mills NJ. Accident investigation of motorcycle helmets. Impact 1996;5:46-51.

[27] Mills NJ, Gilchrist A. The effectiveness of foams in bicycle and motorcycle helmets. Accid Anal and Prev 1991;23:153-63.

[28] Mills NJ, Gilchrist A. Bicycle helmet design. Proc IMechE, Part L: J Materials: Design and Applications: 2006; 2006. p. 167-80.

[29] McIntosh AS, Janda D. Evaluation of cricket helmet performance and comparison with baseball and ice hockey helmets. Br J Sports Med 2003;37:325-30.

[30] McIntosh A, McCrory P, Finch CF. Performance enhanced headgear: A scientific approach to the development of protective headgear. Br J Sports Med 2004;38:46-9.

[31] Spyrou E, Pearsall DJ, Hoshizaki TB. Effect of local shell geometry and material properties on impact attenuation of ice hockey helmets. Sports Engineering 2003;3(25-35).

[32] Caswell SV, Deivert RG. Lacrosse helmet designs and the effects of impact forces. Journal of Athletic Training 2002;37(2):164-71.

[33] Knouse CL, Gould TE, Caswell SV, Deivert RG. Efficacy of rugby headgear in

attenuating repetitive linear impact forces. Journal of Athletic Training 2003;38(4):330-5.

[34] Harrison TI, Mills NJ, Turner MS. Jockeys' head injuries and skull cap performance. International IRCOBI conference, Dublin: 1996; 1996. p. 49-62.

[35] Mills NJ, Whitlock MD. Performance of horse-riding helmets in frontal and side impacts. Injury 1989;20:189-92.

[36] Hunt H, Mills NJ. The Protection of horse riders in impacts with the ground. International IRCOBI Conference, Stockholm: 1989; 1989. p. 157-68.

[37] BSI. EN 1384: 1996 Specification for helmets for equestrian activities. London, British Standards Institution; 1996.

[38] BSI. EN 14572:2005: High performance helmets for equestrian activities. London, British Standards Institution; 2005.

[39] Willinger R, Baumgartner D, Guimberteau T. Dynamic characterization of motorcycle helmets: Modelling and coupling with the human head. Journal of Sound and Vibration 2000;235(4):611-25.

[40] Gilchrist A, Mills NJ. Modelling the impact response of motorcycle helmets. International Journal of Impact Engineering 1994;15:201-18.

[41] Aare M, Kleiven S. Evaluation of head response to ballistic helmet impacts using the finite element method. International Journal of Impact Engineering 2007;34:596–608.

[42] Smith T, Lenkeit J, Boughton J. Application of finite element analysis to helmet design. IUTAM Proceedings on Impact Biomechanics: From Fundamental Insights to

Applications, Dublin: 2005. Springer; 2005. p. 255-62.

[43] ABAQUS. ABAQUS Analysis User's Manual, v 6.7. ©ABAQUS, inc; 2007.

[44] Ozturk UE, Anlas G. Energy absorption calculations in multiple compressive loading of polymeric foams. Materials & Design 2009;30(1):15-22.

[45] Rizov VI. Low velocity localized impact study of cellular foams. Materials & Design 2007;28(10):2632-40.

[46] ABAQUS. ABAQUS Analysis User's Manual. ©ABAQUS, inc; 2004.

[47] Cui L, Kiernan S, Gilchrist MD. Designing the energy absorption capacity of functionally graded foam materials. Materials Science and Engineering A 2009; In press (DOI: 10.1016/j.msea.2008.12.011).

[48] Kiernan S, Cui L, Gilchrist MD. Propagation of a stress wave through a virtual functionally graded foam. International journal of Non-Linear Mechanics 2008;In review.

[49] Avalle M, Belingardi G, Montanini R. Characterization of polymeric structural foams under compressive impact loading by means of energy-absorption diagram. International Journal of Impact Engineering 2001;25:455-72.

[50] Gibson LJ, Ashby MF. Cellular Solids: Structure and Properties. Cambridge, UK: Press Syndicate of the University of Cambridge; 1997.

[51] Huang J, Fadel GM, Blouin VY, Grujicic M. Bi-objective optimization design of functionally gradient materials. Materials & Design 2002;23(7):657-66.

List of Figures

Table 1

Yield and plateau stresses for foams of different densities, as obtained from the constitutive model [47]

Density (kg/m^3)	Yield stress (kPa)	Plateau stress (kPa)
25	180	180~380
50	350	350~760
64	450	450~970
80	580	580~1200
100	720	720~1510
140	1000	1000~2120
180	1250	1250~2720

Table 2

Results of a mesh density sensitivity analysis for uniform liner for two cases: Medium speed (5.4 m/s) frontal impact at a 45° angle, and High speed (7.7 m/s) crown impact. The "low" and "high" in the 1st column indicate the foam block mesh density.

*: Chosen model mesh configurations for the following simulations.

Elements through thickness (foam block mesh density)	Dissipated Plastic Energy (J)	Artificial Energy (J)	Number of Elements	Simulation Time (h)	Vertical Linear Acc. (g)
Front 45° medium speed impact					
3 (low) *	42.6	4.4	6990	1	192
6 (low)	44.2	1.6	52716	3	189
9 (low)	44.7	1	168660	8	189
Crown high speed impact					
3 (low)	85	7.2	6990	1	642
6 (low)	89	5.8	52716	3.5	525
9 (low)	88	5.2	168660	8.5	461
3 (high)	87	6.6	8934	1.2	443
6 (high)*	90	4.1	54660	4	427
9 (high)	90	3.8	170604	9	425

Table 3
Material parameters used in the simulations

Components	Material	Young's Modulus (MPa)	Poisson's Ratio	Density (kg/m^3)
Shell	Linear elastic	7250	0.3	1200
Foam liner	Crushable foam	9.58	0.0	64
Foam block	Elastomeric foam	31.5	0.45	1140
Ring	Rubber	5.0	0.4995	1100
Head form	Rigid	--	--	1249.85
Flat anvil	Rigid	--	--	--

Table 4

Matrix of simulation parameters following standards EN 1384 [37] and EN 14572 [38]

Impact Position	Impact Speed (m/s)
45° side impact	7.7
	5.4
	4.4
45° front impact	7.7
	5.4
	4.4
Normal crown impact	7.7
	5.4
	4.4

Table 5

Densities used in simulations (37 combinations)

Liner Layer	Density (kg/m^3)																		
Inner	25	50	64	80	100	64	64	50	50	64	50	50	50	25	25	50	25	64	64
Middle	25	50	64	80	100	64	50	50	64	50	64	50	25	50	25	25	50	64	25
Outer	25	50	64	80	100	50	50	64	64	64	50	25	25	50	50	50	25	25	25
Inner	25	25	64	25	80	80	80	80	80	80	80	80	80	100	100	100	100	100	
Middle	64	25	25	64	80	80	80	64	50	25	64	64	50	100	80	64	50	25	
Outer	64	64	64	25	64	50	25	64	50	25	50	25	25	80	80	64	50	25	

Table 6
Peak accelerations of best performing helmets with layered foam liner. Reductions in accelerations are given relative to the corresponding accelerations of uniform foam liners of density 64 kg/m^3

Impact position	Energy	Layered density configuration (kg/m^3)	Acceleration ($g = 9.81$ m/s^2)	Reduction in Acceleration
45^o side	1384	Uniform 64	199.0g	--
		Uniform 50	167.6g	15.8%
	Low	Uniform 64	165.0g	--
		Inner 50-25-25 outer	108.5g	34.2%
	High	Uniform 64	317.5g	--
		Inner 80-64-64 outer	327.4g	-3.1%
45^o front	1384	Uniform 64	198.3g	--
		Uniform 50	166.8g	15.9%
	Low	Uniform 64	159.0g	--
		Inner 50-25-25 outer	112.7g	29.1%
	High	Uniform 64	320.8g	--
		Inner 80-64-64 outer	313.9g	2.2%
Crown	1384	Uniform 64	211.8g	--
		Uniform 50	192.6g	9.1%
	Low	Uniform 64	161.9g	--
		Inner 50-25-25 outer	124.8g	22.9%
	High	Uniform 64	428.2g	--
		Inner 80-64-64 outer	403.6g	5.7%