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Impact-absorbing materials in reducing brain vibration caused by ball-to-head impact in soccer

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Abstract

There has been a long debate among researchers on whether soccer heading is capable of causing brain trauma. A recent study suggests that headings exceeding a threshold level of 855 to 1,550 per year, results in microstructural abnormalities in the brain's white matter. This shows that brain trauma is caused by cumulative effect of repetitive headings. The use of protective headgear is one of the suggested preventive measures to protect the brain especially for younger players. Researchers have tested several commercial headgears and found that they are only effective in head-to-head impact, but ineffective in attenuating impact caused by heading. This is due to the fact that soccer ball is compliant in nature relative to the head. The aim of this study is to investigate materials that can be utilised to minimise the acceleration of the brain caused by soccer heading. A vertical drop ball test was conducted on an instrumented dummy skull. The inner cavity of the skull is filled with ultrasound gel that represents the brain. Six impact-absorbing materials were tested to determine the most effective material that reduces the acceleration of the brain substitute. The speed of the ball before and after impact as well as impact duration were measured using high-speed camera. Coefficient of restitution was calculated to ensure the material is not only capable of reducing the brain acceleration, but also maintains heading performance. It was found that polymer kneepad foam is the most effective material that minimises the acceleration of brain substitute whilst maintaining the speed of the ball after impact.

Keywords: soccer heading; head impact; head injury; headgear; impact-absorbing materials;

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1. Introduction

In a soccer game, the players are permitted to use their head to hit the ball in both offensive and defensive play. Many studies have linked purposeful heading in soccer to brain trauma, similar to that found in mild traumatic brain injury (TBI). Both amateur and professional soccer players were evaluated through a series of neuropsychological tests as published by Tysvaer and Løchen (1991), Matser et al. (1999), Matser et al. (2001), Webbe and Ochs (2003) and Witol and Webbe (2003). These tests assess the neurocognitive performance of the players in terms of planning, memory, attention, visual, verbal and so on. It was found that soccer players had scored poorly in the tests as compared to participants who did not play soccer. Frequent headers were also found to have even lower scores compared with non-headers. Thus, the number of headings was reported to be inversely proportional to the neurocognitive performance of a soccer player.

Besides neuropsychological tests, researchers such as Lipton et al. (2013) and Koerte and Ertl-Wagner (2012) have used a more advanced method known as diffusion tensor imaging (DTI) in assessing the neurocognitive performance of soccer players. DTI measures the movement of water molecules along nerve fibres called axons in the brain that is known as fractional anisotropy (FA). Researchers have attempted to assess both amateur and professional soccer players using this technique. These studies have found abnormalities of the white matter of the frequent headers that were similarly found in patients with mild TBI. In addition, Lipton et al. (2013) found a threshold level of 885 to 1,550 headings a year, in which exceeding this number will result in significantly lower FA values that is associated with cognitive impairment in patients with traumatic brain injury.

To further study the mechanics of soccer heading, researchers have attempted to experimentally measure head acceleration endured by soccer players during heading. Bayly et al. (2002) have used human volunteers whilst Naunheim et al. (2003) and Withnall et al. (2005) have used dummy head form in collecting the data. In studies involving human subjects, a series of accelerometers were attached to the subjects' head. From the data obtained, relative motion equation for rigid body was used to calculate the acceleration of the centre of gravity of the head. But using human volunteers limits the experiment to low-speed ball impact to avoid injuries. Thus, dummy head form provides flexibility to researchers to perform ball-to-head impact experiment with higher ball velocities. Ball launching device such as air cannon was used by Withnall et al. (2005) in high-speed ball impact experiment that produces ball velocity up to 30 m/s.

Concerns of possible brain injury in soccer have resulted in the development of headgears with various designs. A study sponsored by FIFA's sports medicine committee conducted by Gray et al. (2009) concluded that headgear is beneficial during head-to-head collisions, but it has no effect on ball-to-head impact. McIntosh et al. (2011) stated that laboratory studies testing headgear to reduce concussion in soccer are inconclusive. The evidence that the headgear could protect the brain while playing soccer is very weak. Naunheim et al. (2003) claimed that currently available commercial headbands were found to be ineffective in attenuating the impact during simulated soccer heading. Headbands tested exhibited no measurable protection at lower speeds or at lower inflation pressures. Another study by Lehner et al. (2010) has shown that when using a commercial headgear (Full90 Premiere), the resulting HIP value is reduced by less than 5%, which suggests that the reduction of the injury risk when wearing Full90 Premiere headgear is very small.

Since previous studies have proved the ineffectiveness of soccer headgear in terms of protecting the brain from the impact caused by heading, we believe that it is important to explore the field and develop a new protective headgear for soccer players that is capable of protecting the brain from unsafe vibration due to heading. We have acquired and tested six impact-absorbing materials. Material A is extracted from a PVC yoga mat. Material B is a lightweight, open cell, cushioning foam that provides extreme impact protection as claimed by its manufacturer. Material C is a flexible mesh sheet that offers shock absorption. Material D is a gel structure made from polyurethane (PU) gel that employs honeycomb structure. Material E is lightweight, durable soft foam that has low compression set. Material F is soft polymer foam taken from commercial kneepad. Unfortunately the material properties of material A, material D and material F are not made available by their respective manufacturers. The properties of all tested materials are listed in Table 1. The aim of this study is to investigate the capability of the aforementioned materials in reducing brain vibration caused by soccer heading. As this study is a preliminary investigation on the development of protective headgear for soccer players, thus no solid conclusion can be drawn from this study other than initial overview of the nature of the problem.

Table 1. Material properties of the tested materials.
(NA : not available)

Properties	Material A	Material B	Material C	Material D	Material E	Material F
Density (kg/m^3)	NA	192.22	500 – 700	NA	260	NA
Tensile strength (kPa)	NA	310	1700	NA	320	NA
Hardness	NA	19	70 – 85	NA	NA	NA
Compression set (%)	NA	<10	<5	NA	NA	NA
Elongation (%)	NA	>145	210	NA	73	NA

2. Methodology

A drop test of a soccer ball was performed, in which a soccer ball is dropped onto an instrumented dummy skull. A fishing line is attached to a standard size-5 soccer ball (model Premier League Strike, Nike, Inc.) through one of its stitches. The fishing line is wrapped around a pulley and the ball is dropped onto the instrumented dummy skull from the height of approximately 2.2 metres as shown in Fig. 1. The chosen height is the highest possible height in the laboratory where the experiment was conducted. Even though this experiment does not replicate actual heading situation in a soccer game, it provides an overview of low-velocity soccer ball impact to the brain.

The dummy skull is rapid prototyped using acrylonitrile butadiene styrene (ABS) as the material. The inner cavity of the skull is filled with ultrasound gel (type EcoGel 200, Eco-Med Pharmaceutical Inc.) up to the foramen magnum that represents the brain. Although ultrasound gel is not an appropriate brain substitute, it provides acceptable first approximation of the propagation of pressure waves caused by translational acceleration. To measure the acceleration of the gel, a tri-axial accelerometer (model 356A67, PCB Piezoelectronics) is placed inside the gel approximately at the centre of gravity of the skull (7 cm from the foramen magnum). It is assumed that the accelerations obtained from the accelerometer represent the brain acceleration.

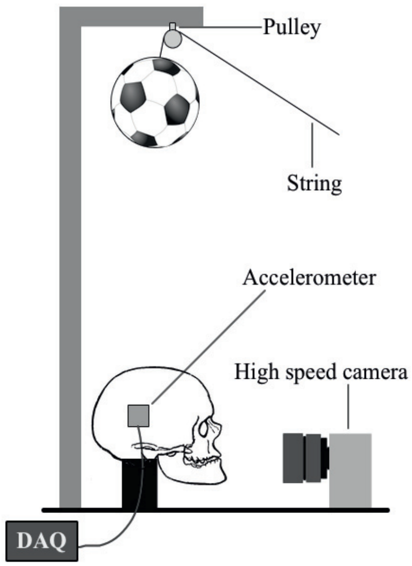

Fig. 1. Soccer ball drop test onto an instrumented dummy skull.

The accelerometer is connected to a data acquisition (DAQ) module (model NI 9234, National Instruments) that is attached to a compact DAQ chassis (model NI cDAQ-9171, National Instruments). The signal from accelerometer is recorded using DASYLab software (version 10, National Instruments). The analogue signals are low-pass filtered (1,000 Hz, Butterworth) and sampled at 5,000 Hz. A high-speed camera (model SV643C, Epix Inc.) is used to capture the motion of the soccer ball to determine its velocity before and after impact, and the duration of impact.

The experiment was first performed without any material being placed on top of the dummy skull. This serves as the control condition for this study, and this condition is labelled as 'bare head'. Each material was then placed on top of the dummy skull one at a time, and the procedure repeated. Duct tape was used to affix the materials to the skull on the side, without altering the location of impact. The experiment was repeated 30 times for each condition, and the average gel acceleration for every case was calculated in Microsoft Excel.

3. Results and discussion

As measured from the high-speed videos, a soccer ball dropped from a height of 2.2 m produces an average inbound velocity of 5.97 m/s. For the 'bare head' condition, the average peak gel acceleration is 6.375 g. It is shown that all materials tested reduced the gel acceleration for the same inbound velocity as shown in Table 1. Material D (PU comb-gel) and material F (kneepad foam) surpassed the rest in reducing the gel acceleration with a reduction of 42% and 48% respectively. The least effective material in this experiment is material B. Although being advertised as an extreme impact protection material by its manufacturer, material B failed to significantly reduce the acceleration of the gel caused by the impact from a soccer ball.

Table 2. Average peak gel acceleration obtained for each material compared with 'bare head' condition.

Material	Peak acceleration, g (± SD)	Difference
Bare head	6.3750 ± 0.8360	-
Material A	4.1354 ± 0.5845	35%
Material B	5.3495 ± 0.6334	16%
Material C	5.2096 ± 0.8467	18%
Material D	3.6698 ± 0.2762	42%
Material E	5.0590 ± 0.7802	21%
Material F	3.3123 ± 0.2505	48%

Whilst all materials tested did reduce the gel acceleration upon soccer ball impact, there is no change observed in terms of the acceleration profile as shown in Fig. 2. All conditions produced almost identical acceleration profiles. It is shown that the use of impact-absorbing material does not affect the decay time of the gel acceleration. The time taken for the gel to stop accelerating is almost identical for each condition. The only parameter affected by the usage of the materials is the peak gel acceleration.

In designing soccer headgear, one important characteristic that needs to be taken into account is how much does the use of the headgear affects the performance of a player. In the case of soccer heading, performance means the speed of the ball after being headed by a player. A headgear could be very effective in minimising the brain acceleration, but if it reduces the speed of the ball after heading, it will be an unfavourable option. Therefore, we use a high-speed camera to record the motion of the ball and measure the speed of the ball before and after the impact, thus calculating the coefficient of restitution (COR) that indicates how much each material alters the ball speed after heading compared with the control condition. Besides ball velocity, contact time was also measured from the high-speed videos as shown in Table 3.

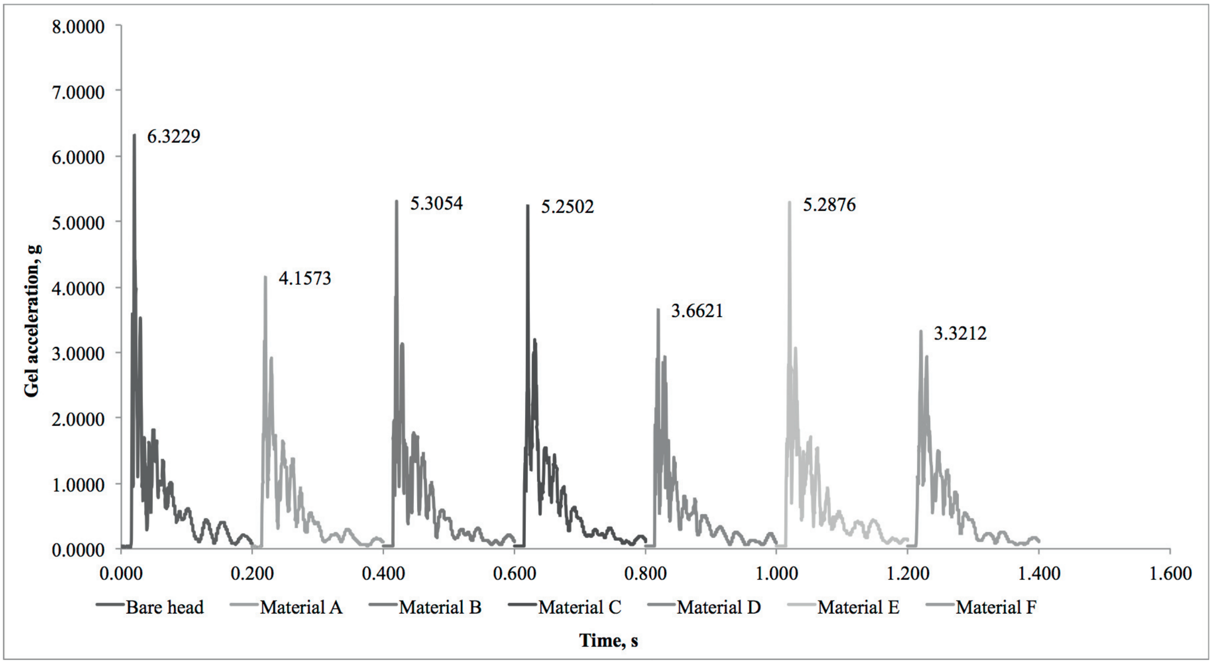

Fig. 2. Gel acceleration profile recorded by the accelerometer for each material.

It is apparent from Table 3 that both material D (PU comb-gel) and material F (kneepad foam) increases the contact time between the soccer ball and the skull by 5% and 8% respectively, which indicates why these two materials produced significant reduction of gel acceleration. However, in terms of COR, material D (PU comb gel) exhibits 17.5% reduction compared with control condition, which implies that the ball speed after heading will be significantly lower when using this gel as the material for the headgear. Therefore, material D (PU comb-gel) is deemed to be an unsuitable material for soccer headgear since it compromises heading performance. Material F (kneepad foam) on the other hand shows no significant difference in terms of COR whilst reducing the gel acceleration by almost 50 per cent. Thus, from this study, it is shown that material F (kneepad foam) is the most effective material in reducing brain acceleration for a low-velocity soccer ball impact compared with other tested materials.

Table 3. Contact time and coefficient of restitution (COR) of the ball.
(Positive sign indicates addition and negative sign indicates reduction from control condition)

Material	Contact time, s	Difference	COR	Difference
Bare head	0.0120	-	0.8919	-
Material A	0.0122	+1.7%	0.8344	-6.4%
Material B	0.0118	-1.7%	0.8907	-0.1%
Material C	0.0126	+5.0%	0.7359	-17.5%
Material D	0.0124	+3.3%	0.8876	-0.5%
Material E	0.0118	-1.7%	0.8716	-2.3%
Material F	0.0130	+8.3%	0.8827	-1.0%

4. Conclusion

This study serves as a preliminary investigation in the development of soccer headgear to minimise the impact of soccer ball heading to the brain. It is too early to conclude which material is the best to be used in the headgear design. Obviously by testing only six impact-absorbing material through a vertical drop ball test onto an instrumented dummy skull is not enough to discover the optimal material for soccer headgear. However, this experiment gave us an overview of what kind of material that could be effective in reducing the acceleration of the brain caused by soccer heading. The polymer foam taken from kneepad (material F) outperformed the rest in our test. Material property testing of the tested foams and finite element analysis (FEA) will be the subject of future work, in which impact-absorbing material will be introduced, covering the scalp of the head model. FEA is the perfect tool to be used in the search of the best material for the headgear since it offers the flexibility, in which one could vary the properties of the material in order to find the most effective material that can minimise brain acceleration during soccer heading at various inbound ball velocity, whilst maintaining the performance of the player.

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