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New generation of headgear for rugby: impact reduction of linear and rotational forces by a viscoelastic material-based rugby head guard

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ABSTRACT

Objectives In the aim to develop a usable and wearable head guard for rugby that could reduce impact energy and lessen the likelihood of concussive and subconcussive injury during play, a combination of viscoelastic materials was employed to develop a guard with similar dimensions to those currently used in international rugby.

Methods The head guard was tested for impact energy reduction following linear acceleration, using drop tests, as required by World Rugby. The head guard was also subjected to pendulum tests, allowing acceleration to be simultaneously measured on two headforms, as well as repeated impacts to mimic ageing and repeated use. Impact following rotational acceleration was determined at two impact locations and at three impact velocities.

Results The viscoelastic head guard (N-Pro) was shown to reduce linear impacts by up to 75% in comparison to the use of a commercially available rugby head guard and repeated impacts did not impair the attenuation of impact energy. Rotational impact energy was also reduced by an average of 34% across three speeds and two sites of impact test sites, in comparison to tested bare headforms.

Conclusions This heralds a new generation of soft-shelled headgear that could help reduce two primary risk factors in sports-induced mild traumatic brain injury: linear and rotational impacts to the head.

What are the new findings?

- Bench testing of the new viscoelastic rugby head guard has shown that it can significantly reduce both linear and rotational impact energy.
- It performs better at reducing impact than the other commercially available scrum caps tested, using test methodology developed by World Rugby.

How might it impact on clinical practice in the near future?

- Use of these N-Pro head guards could potentially help reduce the severity of traumatic brain injuries sustained during play in contact sports such as rugby by reducing the force from linear and rotational accelerations.

INTRODUCTION

There has been much focus on the phenomenon of sports-related mild traumatic brain injury (mTBI), with growing fears that prolonged exposure to head impacts in sports may lead to long-term cognitive, behavioural and neuropathological effects. In rugby union, concussive hits have been rising in incidence (figure 1)[1–5] and were shown to occur at a rate of 20.1 concussions per 1000 player hours by the England Professional Rugby Injury surveillance project in the 2016–2017 season[4] and players are known to be exposed to numerous subconcussive hits throughout their careers.[6] This has prompted calls for action by international sports bodies, such as World Rugby, to address a growing need for education and prevention strategies in ensuring that risk from head injury can be at a minimum.

Concussive and subconcussive injuries, both of which fall into the mTBI spectrum as defined by the Glasgow Coma Scale, arise from blows to the head, or neck, resulting in deformation and movement of the brain tissue within the skull. Such blows can result in a plethora of somatic, emotional and cognitive symptoms such as (but not necessarily including) loss-of-consciousness, visual disturbances, balance difficulties, dizziness, memory loss, difficulty in concentration, irritability and confusion, often in the absence of any evident structural abnormality using standard neuroimaging techniques. While there is huge interindividual response in the severity and number of symptoms experienced, it is evident that, if the impact energy to the head can be lessened, the resulting so-called *neurometabolic cascade*,[7] which has both short-term and long-term damaging effects, can be reduced. This is particularly important in sports where players are subjected to

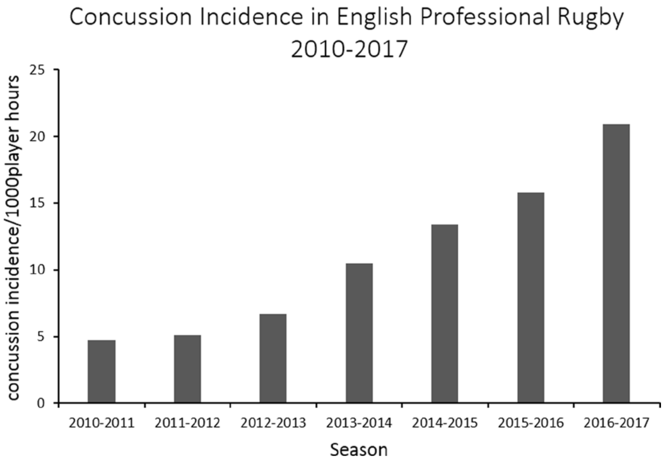

Figure 1 Increase of concussion incidence in English professional rugby between 2010 and 2017.

repetitive trauma over a sports season or, in some cases, a lifetime. A paper by King *et al* has estimated the number of impacts to be 77 per player per match in amateur rugby union[8] suggesting that mild brain trauma may be occurring even in the absence of concussion symptoms, and this can have very serious long-term health consequences.[9]

The issue of headgear use in contact sports has always been a divisive one, with little compelling evidence that hard-shelled helmets, traditionally used in ice hockey and American football, have any protective effect against mTBI and may even exacerbate the neuropathological damage.[10] Similarly, the soft-shelled foam-based head guards, used in rugby, have not shown any protective effect against mTBI and serve mostly to protect against cuts and abrasions. What further confounds the matter is that there is no agreement, across different standards agencies and international sporting bodies, about what constitutes an acceptable level of impact attenuation by sports headgear. Table 1 illustrates the different impact attenuation values required by ASTM International for different sports and leisure activities. (In the absence of an ASTM standard for rugby, the regulations from World Rugby regarding player's clothing, are included as a comparator.)

However, advances in polymer technology have meant that soft foam based rugby headgear, capable of reducing impact energy, can be developed. Viscoelastic polymers, as implied by the name, have both viscous and elastic properties when undergoing deformation and are used worldwide for the purposes of shock absorption and vibration reduction.[11] The proprietary material, Defentex, from which a new type of head guard (the N-Pro) has been made, contains layers of viscoelastic polymers that have been shown to absorb impact in the absence of a hard outer shell, unlike other sports 'helmets'. It is composed of interspersed soft elastic segments, which absorb energy, and harder segments which confer hardness and rigidity and help to retain the form of the material.

It is critical to assess whether this headgear, designed specifically for use in rugby, actually has the ability to absorb impact energy and, in doing so, reduce the forces being transferred to the brain tissue during play. A series of linear impact tests was carried out on the N-Pro head guard and the results compared with those from two of the most popular head guards, of the 210 styles currently having the World Rugby approval mark (http://playerwelfare.worldrugby.org/?documentid=52). The head guard was also tested for its ability to attenuate impact when subjected to rotational accelerations.

Table 1 Test standards for peak acceleration of impact in protective headgear

Sport or leisure activity	Peak acceleration (g max)	Body	Reference
American Football	Must not exceed 300g	ASTM	F717-10
Horse sports/horseback riding	Must not exceed 300g	ASTM	F1163-15
Cycling & roller-skating	Must not exceed 300g	ASTM	F1447-12-
Skateboarding/trick roller-skating	Must not exceed 300g	ASTM	F1492-08(2015)
Speed skating	Must not exceed 300g	ASTM	F1849-07(2012)
Downhill mountain bike racing	Must not exceed 300g	ASTM	F1951-15
Recreational snow sports	Must not exceed 300g	ASTM	F2040-11
BMX biking	Must not exceed 300g	ASTM	F2032-15
Soccer	Must not exceed 300g	ASTM	F2439-06 (2016)
Martial arts	Must not exceed 80g	ASTM	
Falling	Must not exceed 300g	ASTM	F2397-09
Low energy striking impact	Must not exceed 50g	ASTM	F2397-09
High energy striking impact	Must not exceed 150g	ASTM	F2397-09
Rugby	Must be greater than 200g	WR	Regulation 12

ASTM International, American Society for Testing & Materials; WR, World Rugby.

Test battery 1

Effects of reducing linear impacts were tested by Anecto Ltd an independent ISO 17025 Accredited Test Laboratory based in Galway, Ireland. This company was chosen after comparing the test modalities used by a number of companies who carry out impact testing of headgear. Anecto Ltd employ a sampling frequency of 1MHz.

Anecto carried out both drop and pendulum tests. All testing was carried out on headforms with the N-Pro, and bare headforms were used as controls. Testing was also carried out on two of the best-selling rugby head guards, hereafter referred to as CA#1 (commercially-available #1) and CA#2 (commercially-available #2).

Drop tests

All drop tests were carried out in accordance with World Rugby Regulation 12, Schedule 1, Section 4.3 https://www.worldrugby.org/handbook/regulations/reg-12/schedule-1?lang=en (figure 2A), with measurements taken from 'crown', 'temple' and 'forehead' (figure 2B) of the head guard.

All headforms used were compliant with EN960. For the crown area, a single drop measurement was made, but for temple and forehead sites, max *g* force was measured at two sites (figure 2B) and the average value reported. For all drops, the following parameters were used:

Energy level=13.8 J, Drop=300 mm, Head mass=4.7 kg. All recorded values are the mean of resolved *g* values from three successive drops (with all drops lying within ±10 g of the mean value).

Pendulum tests

Pendulum tests were carried out using equipment customised by Contego sports to allow two headforms (size J compliant with EN960) to be tested. This allowed measurement of peak linear acceleration (PLA) in two different scenarios: (1) one headform stationary and one moving and (2) both headforms moving (figure 2C). Each test was carried out six times and the average value determined.

Repeated impact tests

In order to simulate ageing of the headgear and to address the problem of players being subjected to a large number of concussive and subconcussive hits, the N-Pro was subjected to repeated pendulum impacts, using the customised apparatus shown in figure 2B (iii), at an acceleration of 20 g, to simulate 1, 2 and 3 years of use. In total, the N-Pro received 1920 impacts.

Test battery 2

Since it is known that many of the neuropathological changes in the brain, resulting from concussive and subconcussive impacts, are due to rotational forces,[12] it was deemed necessary to test the ability of the head guard to reduce impacts when subjected to rotational acceleration. This testing was carried out by the Department of Biomedical Engineering & Mechanics, Virginia Tech, Blacksburg, Virginia, USA. Twenty-four impact tests were carried out using a custom head-to-head impactor.[13]

The headgear was tested on NOCSAE headforms mounted on Hybrid III necks, instrumented with linear acceleration and angular rate sensors. Two impact locations, representing most common head-to-head impacts, were tested using three impact velocities, representing a range of impact severities from low to high risk. Bare head-to-head tests were carried out as a control range. All tests were carried out twice.

Statistical tests

Statistical analysis was carried out on PLA for the three head guards at five sites using a two-way ANOVA for balanced data. Interval estimates for the pairwise difference between head guards (using Tukey Honest Significant Differences). Comparison of results in the pendulum testing was carried out using Student's t-test.

RESULTS

Test battery 1a—drop tests

Drop tests showed that the N-Pro is better at attenuating impact than CA#1 and CA#2 with peak acceleration being reduced to below 200 g in all areas of the headgear tested (figure 3A). In the crown drop test, the N-Pro resulted in 67% and 72% reductions in impact acceleration in comparison to CA#1 and CA#2, respectively. In the temple drop test, the average impact reduction was 35% compared with CA#1 and 55% compared with CA#2. In the forehead drop test, only the N-Pro attenuated impact acceleration to a large degree, with both hits resulting in a measured *g* max of approximately 100 g. This contrasted with the other head guards tested whose measured PLAs were all 300 g or greater, indicating only minimal impact protection. The N-Pro resulted in a reduction in impact acceleration of 71% and 76% in comparison to CA#1 and CA#2, respectively. Statistical testing showed the N-Pro had a significantly lower mean PLA compared with CA#1 and CA#2 (p=0.02 and p=0.002, respectively) with no evidence of a difference, on average, between CA1 and CA2 (p=0.16). It is noted that impact reduction performance varied across all testing sites, for all headgear, with the N-Pro demonstrating the smallest variation.

Test battery 1b—pendulum tests

To measure the effect of impact on the wearer of the headgear and in another player, should a head-to-head impact occur during play, a customised impactor was made by Anecto according to specifications by Contego Sports Ltd. No significant difference was seen in PLA measurements from when one headform was moving (1HFM) and when both headforms were moving (2HFM) (data not shown) or between PLA values measured on headform 1 (HF1) and those on headform 2 (HF2) (data not shown). Pendulum testing demonstrated that the presence of the N-Pro on one

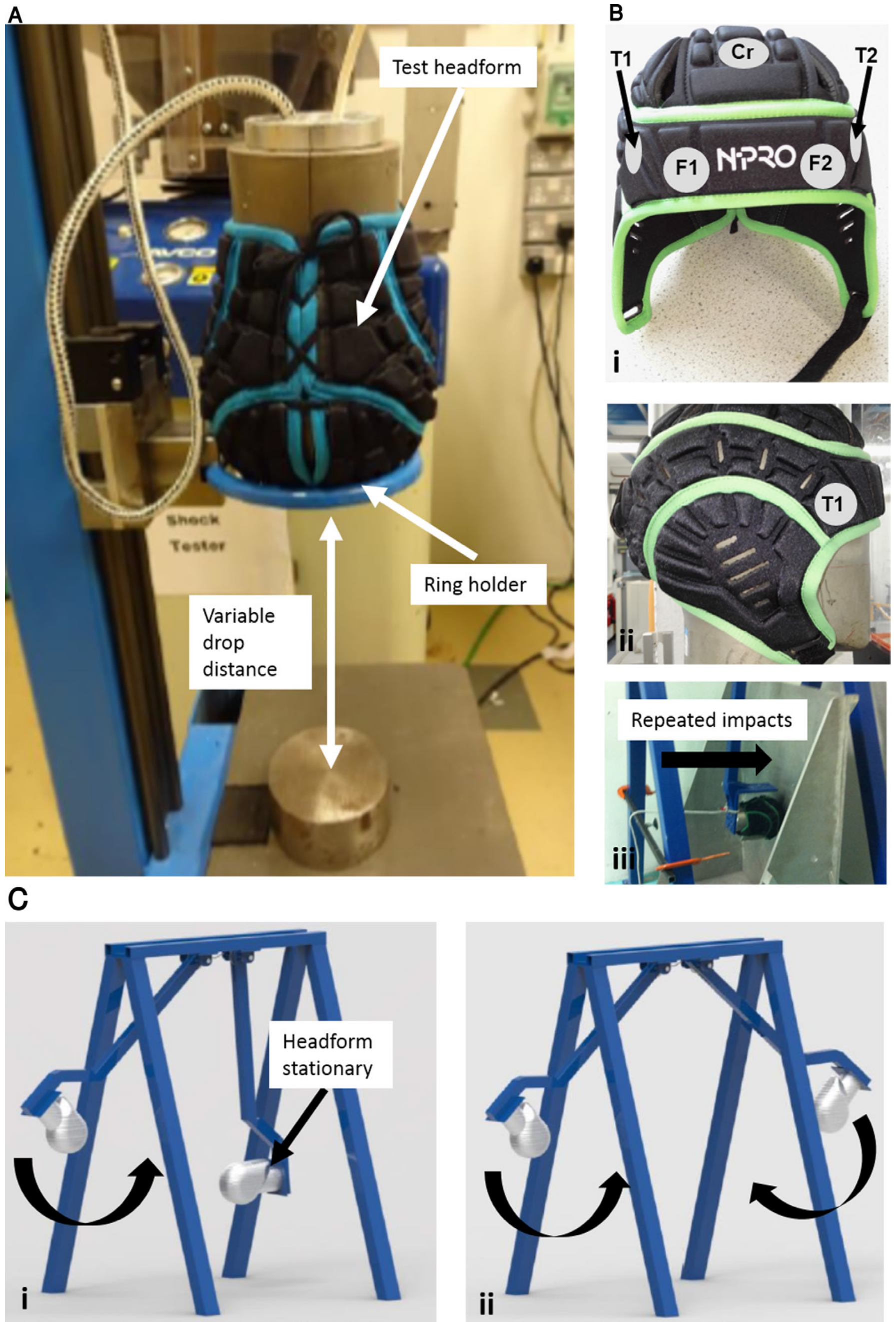

Figure 2 (A) Customised equipment used for drop tests: Headforms (4.7 kg), either without protection or with a head guard were dropped a distance of 300 mm and PLA measured using a triaxial accelerometer. (B) sites on head guard where max *g* force is measured (i) front view of head guard showing forehead, temple and crown sites (ii) side view showing temple (iii) Customised pendulum testing equipment for carrying out the repeated impact testing. (C) Customised pendulum testing equipment where impact testing on two headforms can be carried out simultaneously. This allows testing of impact attenuation with (i) one stationary head and one moving head and (ii) two moving heads. (D) Cr=Crown drop measurement site; F1=Forehead drop measurement site #1; F2=Forehead drop measurement site #2; T1=Temple drop measurement site #1; T2=Temple drop measurement site #2. PLA, peak linear acceleration.

headform resulted in reductions in PLAs measured on both headforms. The measured impacts were lower in this scenario than when both headforms were bare or one headform was protected by CA#1 (figure 3B).

Similarly, the use of at least one N-Prohead guard reduced impact in both headforms, irrespective of whether the other headform was unprotected or protected by CA#1. CA#1 on one headform, with the second headform unprotected, did not show this degree of impact attenuation (figure 3B).

Test battery 1c—repeated impact tests

Crown drop tests on the N-Pro (figure 3C), to simulate ageing of the head-guard showed that there was no

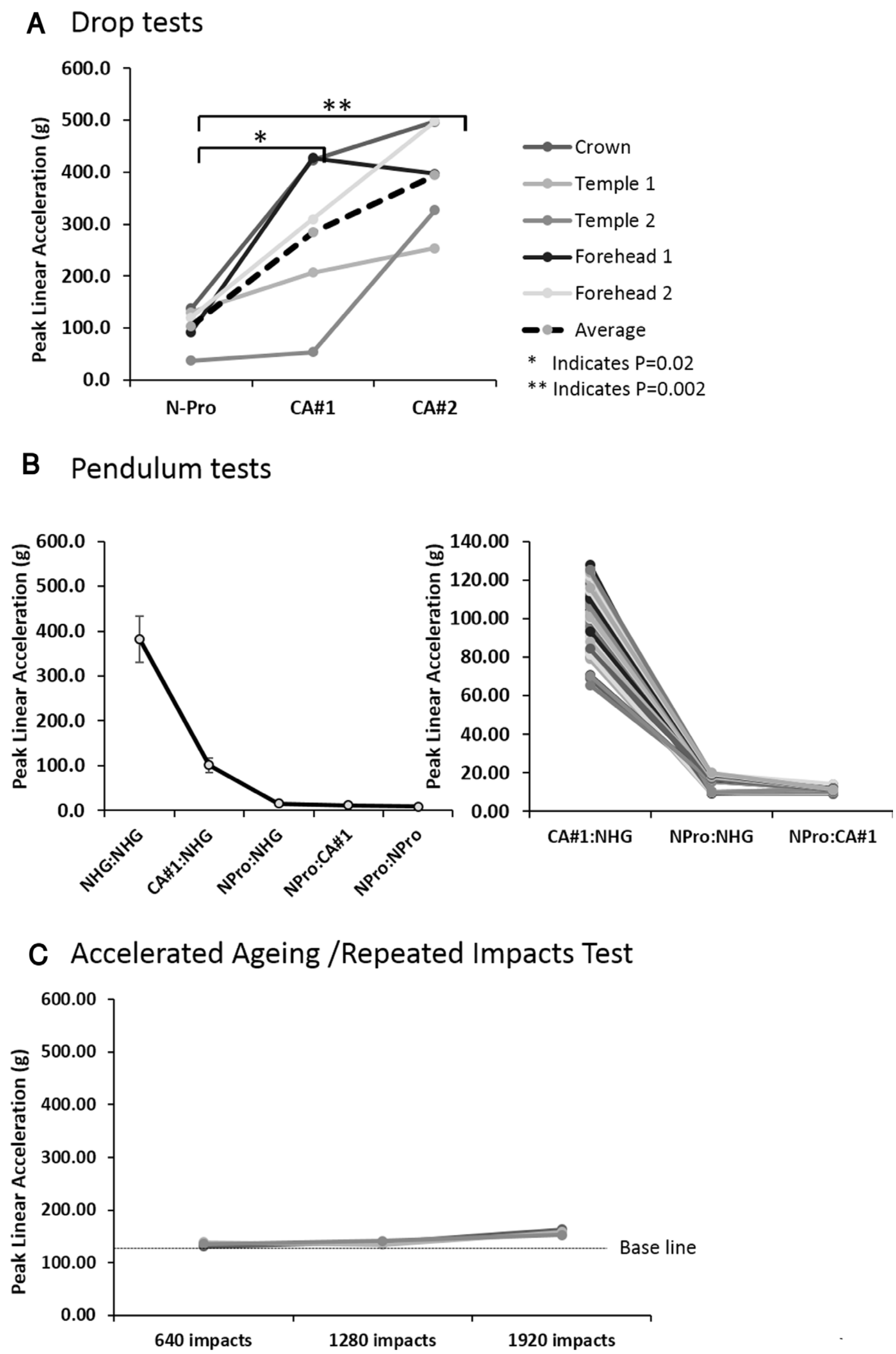

Figure 3 (A) Average measured max *g* force following drop tests on forehead, temple and crown sites of head-forms with N-Pro, CA#1 and CA#2. (CA#1 and CA#2=commercially available head guard 1 and commercially-available head guard 2, respectively). (B) Average measured max g force in pendulum tests with two headforms. (C) average measured max *g* force prior to testing and after 640, 1280 and 1920 impacts to the N-Pro head guard, respectively. NHG, no head guard.

change in measured PLA values after 640, 1280 and 1920 repeated impacts, respectively.

Test battery 2—rotational acceleration tests

At two of the impact velocities tested, and in both head locations, N-Pro was shown to reduce the impact due to rotational accelerations in comparison to bare heads. Impact reductions of 35% and 58%, after rear and side impacts respectively, were achieved at a velocity of 7.2 km/hour, and at 10.8 km/hour rear and side impacts were reduced by 23% and 39% (figure 4).

DISCUSSION

The phenomenon of sports-related head injury has received increasing attention in the last two decades, highlighted by the recent publication of the consensus statement from the 5th International Consensus Conference on Concussion in Sport in Berlin,[14] concerning detection, diagnosis, management, risk reduction, recovery time, treatments and long-term effects of concussion associated with sport. The issues are particularly relevant to rugby union where there is a rise in the

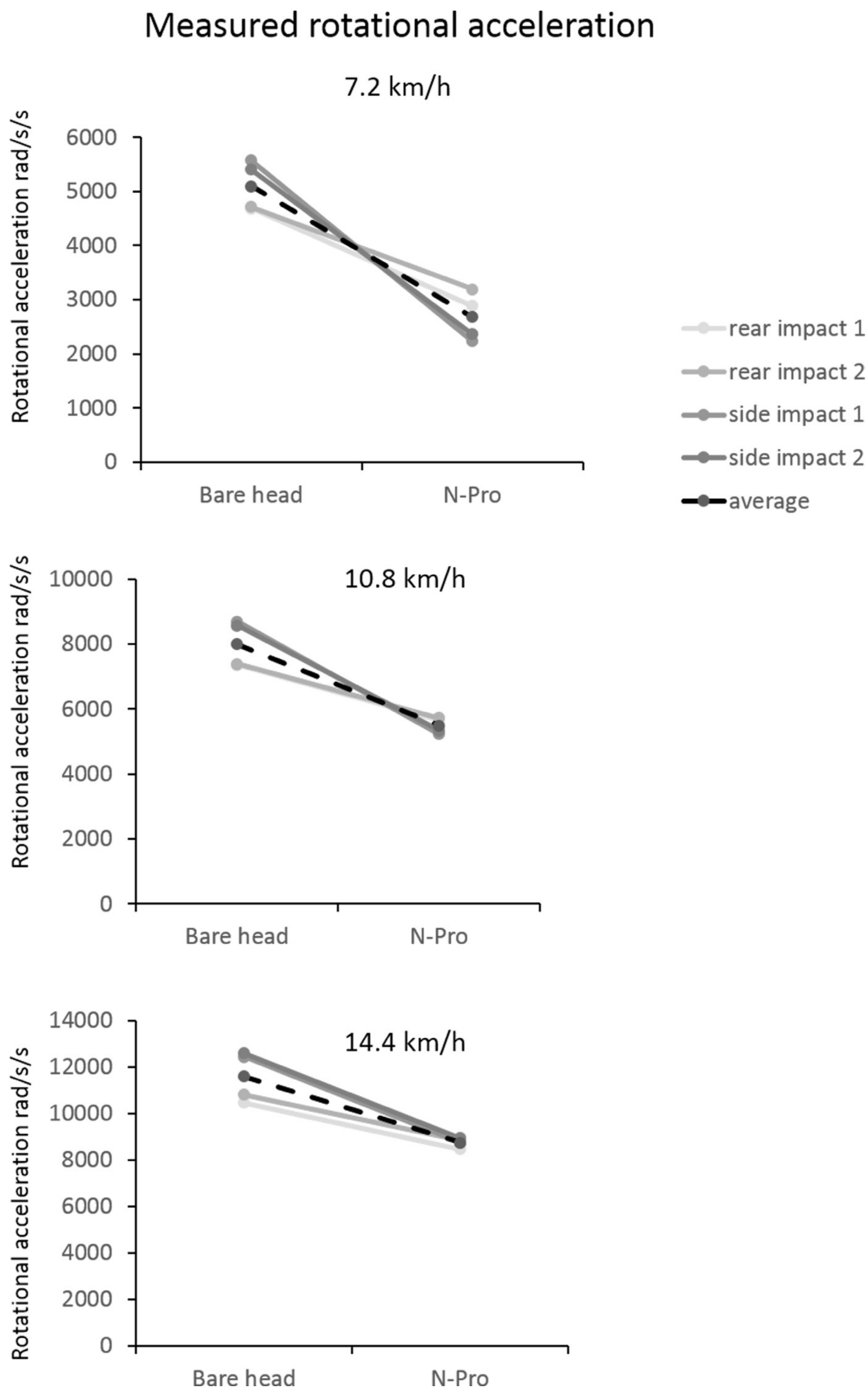

Figure 4 Measured rotational acceleration (rad/s/s) at rear and side of headforms at three different test velocities. values shown are for bare headforms and headforms with N-Pro.

number of reported concussions[1–5] and where concussion rates among youth players have been reported as being the highest among a number of contact sports including ice hockey, lacrosse and American football.[15]

The issue of protective headgear use in rugby has always been a contentious one, with many reports claiming that existing head protection does little more than prevent cuts and abrasions.[16–18] However, several studies have shown that players who wear head guards suffer fewer head injuries[16] and given that the structural and cellular damage resulting from head-impact is directly proportional to the peak acceleration reaching the head, it would seem logical to use headgear that could dissipate impact forces.

In this study, we have investigated the impact attenuation properties of a new viscoelastic foam rugby head guard (N-Pro, Contego Sports) in terms both of applied linear and rotational forces. Initial testing, using the standard drop test (as required by World Rugby Regulation 12) showed that the N-Pro was capable of reducing

PLA at all three sites on the head guard and performing significantly better CA#1 and CA#2. It is of note that the large variation in performance in this particular regulatory test, across testing sites (which was smallest in the N-Pro), may indicate that further and more rigorous testing regimes are introduced by world sporting bodies.

Moreover, in a specially designed two-headform test, to determine impact attenuation effects both for the N-Pro wearer and the person with whom they come in contact, the N-Pro was found to reduce the measured max g force entering both the headforms, irrespective of whether the other headform was bare, covered with CA#1 headgear or covered with another N-Pro head guard. The recorded PLAs were the same in both 'one head moving' and 'two heads moving' scenarios. Such results show the efficacy of the equipment at attenuation of impact and the inherent safety of the head guard in that impact absorption does not lead to changes in its physical properties that could result in injury of another player.

Of additional interest is the fact that, in this set of tests, all measured impacts on set-ups using the N-Pro were less than 20 g whereas tests on CA#1 resulted in measured *g* values ranging from 95 to 110. In effect, the use of the head guard has reduced the impact from 'moderate' (66–106 g) to 'mild'.[8] Also of interest is that fact that, when using two N-Pro head guards the measured PLAs were less than 10 g which is the actual cut-off point for some player-worn accelerometers, below which acceleration the impact is not registered.[8]

Repeated impact tests on the head guard, to determine performance of the headgear over time, were also relevant, given that the number of impacts to which a player is exposed, whether resulting in concussion or not (ie, subconcussive blows) has been correlated to development of chronic health problems such as depression, cognitive impairment and chronic traumatic encephalopathy.[9 19] Furthermore, King's research group, using instrumented mouthguard acceleration measurements on amateur rugby union players, estimated the number of >10 g impacts to the head, per player position per match to be 77.[8] Although in vivo testing of wearable sensors have shown that they may overestimate impact values, and that there is difficulty in determining the exact number of impacts during play, the ability of the N-Pro head guard to reduce PLA after 1920 impacts, shows its long-term performance to be markedly better than other commercially available head guards whose impact attenuation properties were shown to be reduced up to 50% by repeated impacts.[17]

While most standards testing bodies and international sports organisations have rules regarding allowable PLAs, there is mounting evidence that it is the rotational (angular) forces resulting from oblique or glancing head blows[12] that lead to the deformational brain movements thought to result in the plethora of cellular effects that lead to chronic disease.[20–24] Using well established techniques for measuring rotational acceleration[13] the N-Pro was shown to reduce impact by an average of 34%, across three impact speeds and two impact sites (range: 19%–58% 95th percentile 39%) compared with bare headforms.

The ability of the N-Pro to attenuate both linear and rotational accelerations marks a new departure for the use of soft-shelled headgear in impact sports such as rugby. While previous publications have either refuted the benefit of foam-based head guards or determined that the headgear would have to be of a thickness beyond what would be acceptable on the field (McCrory *et al*), impact testing of the N-Pro clearly demonstrates that novel use of a proprietary formulation using visco-elastic materials may help in reducing dangerous linear and rotational forces that are experienced on the field. Indeed, testing of the N-Pro foam on a rodent model of mTBI has shown that it can prevent impact-associated behavioural and blood biomarker changes.[25] While it is evident that there is much still to be learnt about mTBI and how repeated impacts can have long-term pathological sequelae, the known linear relationship between impact force and injury provides one rationale by which injury can be minimised. Nothing can provide 100% protection against sports-related head injuries but the development of a head guard with such excellent impact attenuation properties provides great hope, at least, for development of equipment that could reduce head-injury risk in a hugely popular game.

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