JOCKEYS' HEAD INJURIES AND SKULL CAP PERFORMANCE

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ABSTRACT

The Jockey Club collected skull caps after jockeys suffered concussive head injury. 56% of the newer design of cap showed impact sites near the lower rim of the cap, indicating that it offers improved protection. The impact damage of the caps was described. For some caps, head linear accelerations were estimated to about 100 g. Videos showed that several jockeys somersaulted as they hit the track, and that there was significant head rotation. For the caps with minor liner damage it was not possible to decide if concussion was caused by linear or angular head acceleration.

JOCKEYS HAVE USED protective skull caps for many years, but the design has changed with time. Many recreational riders in the UK also wear jockey skull caps, since they are perceived to be manufactured to a higher standard than BS 6473:1984[1] for general riders. Mills and Whitlock[2] found in 1989 that the performance, of jockey skull caps complying with British Standard BS 4472:1966, was poor for impact sites low down on the skull cap, because of the soft foam in the headband area. These were injuries to recreational riders; some occurred when riding on hard road surfaces, others from impacts with the branches of trees. The riding position of jockeys differs from that of recreational riders, as does the speed and the surface ridden upon. This paper examines the performance of skull caps when worn in races, by professional or amateur jockeys.

The Jockey Club Accident Fund sponsored research to see the state of caps worn by jockeys, and whether improvements in cap design have affected the head injury statistics. The club is the regulatory body for horse racing in the UK, and can insist on the use of protective equipment. For many years jockeys have been required to wear BS 4472:1988 skull caps[3]. Many of these were manufactured by Champion Manufacturing (Safety Headwear) Ltd, Cardiff with the tradename 'Professional Jockey Skull Cap'. Negotiations between the Jockey Club and Champion lead to an improved design, the 'Champion Euro', which was marketed from April 1994. Since February 1996 jockeys have been required to wear this or the 'Champion Euro Deluxe', which has minor changes in the internal comfort padding. It provides greater protection in the lower parts of the cap, since the rigid polystyrene foam liner extends to the lower rim, rather than a softer polyethylene foam being used for the 50 mm wide headband area, and it should pass the draft European standard[17]. The shell material changed from glassfibre reinforced thermosetting plastic (GRP) to injection moulded ABS thermoplastic (Acrylonitrile butadiene styrene copolymer). Figure 1 shows vertical cross sections, in the ear-to ear plane, of the two caps. The outer shell of the cap is intended to prevent sharp objects such as a horse's hoof penetrating the foam and allowing the localised impact force to fracture to the skull. The shelll should also, by resisting localised bending, absorb energy and increase the area of foam crushed when a sharp object hits the cap. It absorbs some energy when it is deformed. The foam liner absorbs the majority of the impact energy, by crushing when it is compressed. This provides the skull with an increased stopping distance, so the deceleration of the brain is smaller than without the cap.

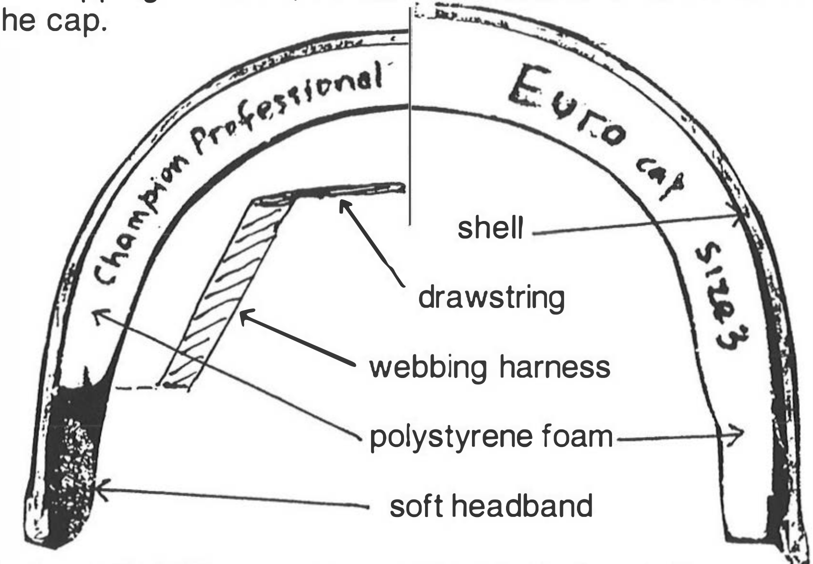


Fig 1. Sections of a) Champion professional, b) Euro in the ear to ear plane.

Foster et al[4] showed in 1976 that the repeated concussions suffered by some National Hunt Jockeys caused epilepsy or intellectual deterioration. Skull caps at that time had only thin layers of cork inside the GRP shell, and there was an air gap between the inside of the shell and the top of the head. The main energy absorbing mechanisms were the stretching of the hamess and the bending of the shell. A survey of jockey injuries in the USA[5] showed that the majority (64%) are fractures, and 13% are concussion, a higher rate than in American football or boxing. Closed head injuries can cause functional brain damage (concussion) or structural damage (haematomas or diffuse axonal injury). Repeated concussive injuries to riders can produce permanent brain damage [6].

Concussion severity is classified by the Jockey Club[7] and appropriate action recommended:-

Mild - stunning or disorientation, without loss of consciousness. The jockey should not ride for 2 days after a full recovery to normal consciousness and mental ability, and the cessation of any headaches.

Moderate - a loss of consciousness for less than 1 minute, usually associated with memory loss of events immediately before and after the accident. Jockeys should undergo a medical examination, not ride for 1 week, and be cleared by a doctor if neurological symptoms persist.

Severe - a loss of consciousness in excess of 1 minute. A thorough neurological examination and observation should follow and the jockey should not ride again until given medical permission.

Jockeys may be tempted to resume riding before they are medically fit to do so. The average jockey's career in the U.S.A is seven years[8]; repeated injuries and the pressure of having to reduce weight cause early retirement; the jockeys suffered more than 100 deaths and 37 paraplegic cases in 1950-1987. In the UK there have been 8 deaths in the last 25 years. In the U.K., the Jockey Club has taken several measures to improve safety; it has introduced the new cap design, re-designed guide-rails, and upgraded medical supervision at the track side[9].

METHODOLOGY

COLLECTION OF CAPS was organised by Dr Turner, the Chief Medical Adviser of the Jockey Club. It started in October 1994, when jockeys sent in caps that had been involved in falls, and is ongoing. The caps were collected if a jockey was concussed in a race, and replacement caps of the new design were provided. The horse-owner's silk cover on the outside of the cap was not collected, since owners employ different jockeys. Hence any grass or mud marks on the silk were not recorded.

VIDEOS OF RACES were recorded professionally by Racetech, using the Betacam system which records 50 high definition frames per second, either with telephoto lenses, or from a camera car driving parallel to the course. The relevant parts of the videos were photographed frame by frame with a 35 mm camera, and the trajectories of the riders traced from the prints. Size markers were needed in the vicinity of the jockeys to establish the velocities. The rails which are 4 foot high and which usually have posts at a spacing of 8 feet, are useful markers. The velocities of the horses were measured as about 15 m/s.

EXAMINATION OF CAPS The sand-containing black paint was removed from the GRP shells using acetone. Part of the paint transferred into the cracks in the GRP, rendering them visible. When the shell was held up to a bright light source, areas of delamination between the layers of glass cloth appear more opaque than the undamaged shell. It was not easy to remove the paint from ABS shells. There was rarely any cracking of the ABS, but localised whitening sometimes occurred in areas where there had been high tensile strains.(light is scattered from crazes which form around the micron-sized rubber spheres in the plastic). The 2 mm thick layer of soft foam, taped to the lower edge of the Euro cap liners, was removed to allow examination of the liner. The damage location on the shell and the areas and depth of crushing of the foam, on both inner and outer surfaces, were recorded. The liner damage, categorised by the area of crushing at the main impact site, was
severe if the area was greater than 2500 mm^2,
moderate if it was greater than 1000 mm^2,
minor if the area was smaller.
Samples of foam were cut out for density measurement. The local stiffness of the shells was measured, by supporting the inside of the shell on three posts, spaced by 41 mm in an equilateral triangle, with the outside pressing on a flat steel plate. A slow rate of loading was used, and the shell stiffness was defined as the force needed to cause a deflection of 1 mm. A reduction in stiffness indicates that the shell has been damaged.

TESTING RESIDUAL PERFORMANCE Ten caps, where there was clearly crushing of the foam liner, were re-impacted using a fixed headform test rig. The aluminium headform could be tilted far more than the wooded headform in BS 4472, so that the accident impact sites could be re-impacted with a flat steel striker of mass 5 kg. The velocity of the vertically-falling striker is aimed at the centre of mass of the headform. Computer analysis of the striker acceleration versus time was used to produce graphs of the force exerted by the striker versus the deflection of the upper surface of the cap shell. In BS 4472 :1988 the impact kinetic energy is 110 Joules for 'front' and 'rear' sites and 80 J for the 'side' impact sites (figure 2). The test criterion, that the force transmitted to the headform is less than 20 kN, is less onerous than that for most other types of helmet, for which the allowable headform acceleration is 250 or 300 g. A force of 20 kN on a head of mass 5 kg produces an acceleration of 400 g.

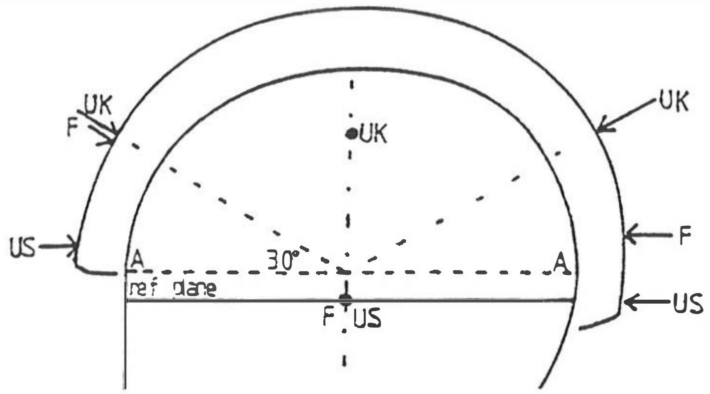


Figure 2. Impact sites in BS 4472 (UK.) compared with French and US sites

ANALYSIS OF DAMAGE is in its infancy, as laboratory test facilities only reproduce a few of the features of the fall. Impact test rigs, used in standards, have rigid strikers or anvils rather than a deformable grassy surface, and the impacts have no velocity component tangential to the cap surface. Videos of falls show that there is always a velocity component of the jockey parallel to the ground, that is higher than the vertical velocity component. The jockey often tumbles with his body in a 'foetal' position, so the motion kinematics are complex.

We analysed the liner damage caused by the velocity component normal to the cap surface. Smith et al[10] selected pedal cyclists' helmets where the main damage was from an impact normal to the helmet surface, rejecting helmets where abrasion marks indicate a large tangential velocity component. They reproduced the damage, using impacts at a range of velocities, while measuring the headform acceleration. Our alternative approach is to measure the area of crushing on the helmet, and to use a mechanics analysis to calculate the force that cause the crushing. However, the nature of the damage depends on whether a rigid road surface or soft grass is hit . The protection afforded by riding helmets was shown to be increased by the deformation of the ground[11]. The relationship between the area of crushed foam and the peak deflection of the foam also depends on nature of the surface hit. For soft surfaces the area can be large while the peak crushing distance is small. If the ground is very soft, the contact area between the cap and the ground can be very large, and the yield stress of the foam may not be exceeded. In this case the foam does not provide any head protection.

We intend to investigate the effects, of the velocity component tangential to the cap surface, on the impact response. The helmeted instrumented headform will fall vertically onto an surface which moves horizontally on bearings(Figure 3). If the surface deforms significantly, the helmet may rapidly stop sliding on it, and inertia will make the headform rotate. We have constructed a smaller test rig, in which a slice of a cycle helmet makes an oblique impact with a rough-surfaced rigid turntable, rotating at 8 m/s. High values of the rotational acceleration of the headform slide were recorded [12].

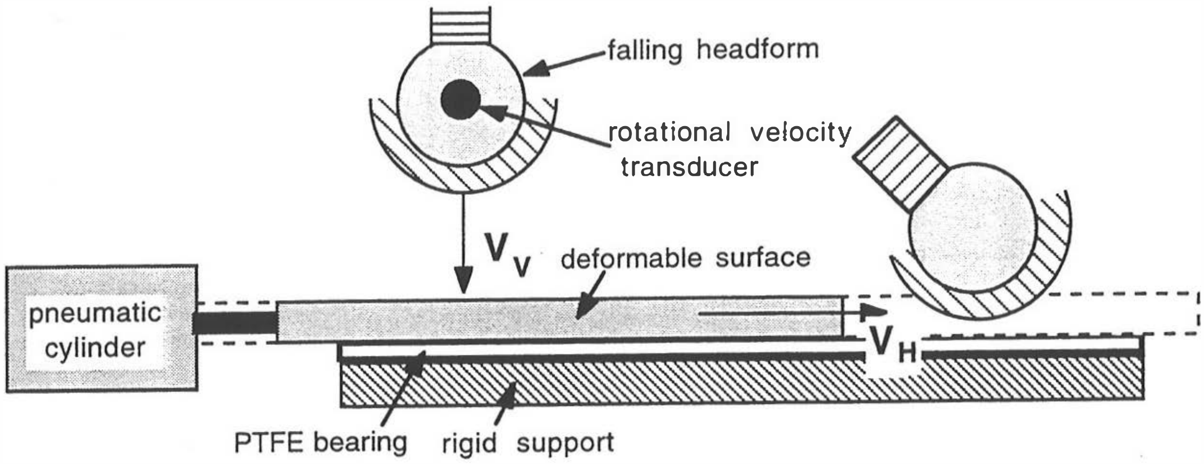


Figure 3 Test rig for oblique impacts. The second position shows the cap indenting the soft test surface, and the headform rotatation.

RESULTS

CAP DAMAGE Figure 4 shows the liner damage to one cap of each type. The main area of foam crushing is on the left side in both cases. For the Champion Professional cap there is cracking of the GRP above the impact site. In figure 4a the impact is over the lower edge of the liner, which lies above the soft headband. For the Euro cap, the crushing is at the lower edge of the liner, which extends to the base of the the cap. The caps, main impact sites and severity of concussion are listed in table 1.

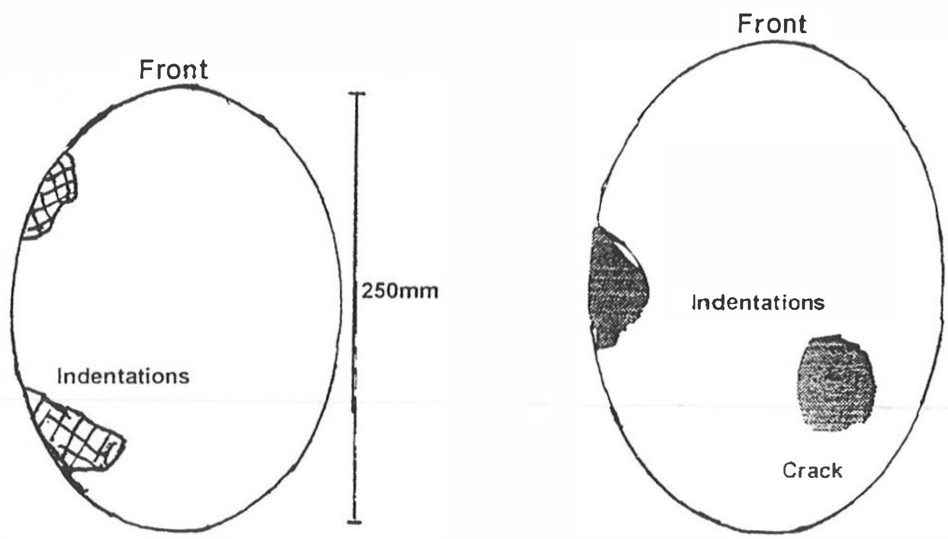
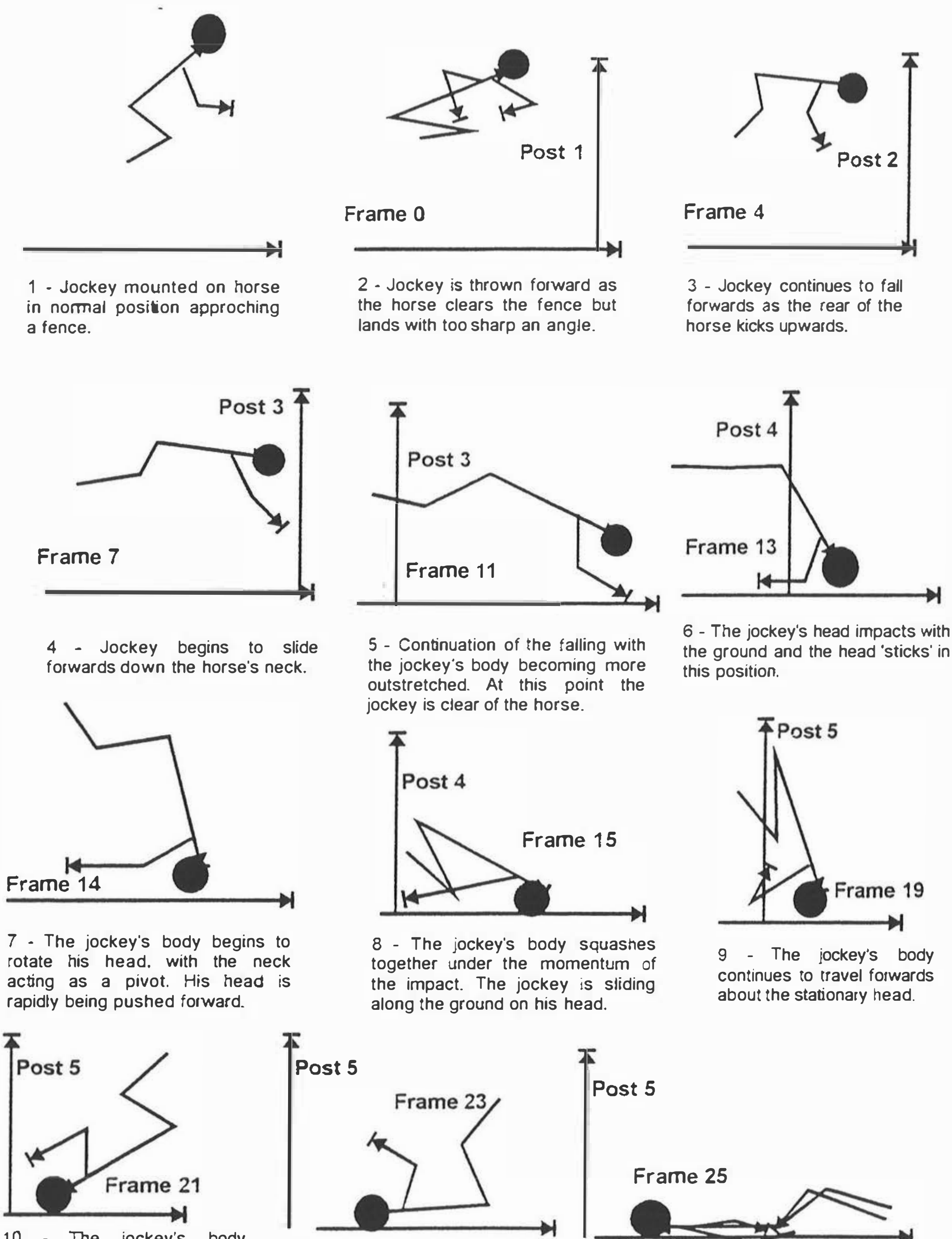


Fig. 4. External foam liner damage of a) GRP cap #5, b) Euro cap #1of table 1

VIDEOS OF FALLS Videos were obtained of the falls from no. 26 onwards, but in some the motion of the jockey is obscured. Figure 5 shows the forward somersault of jockey #26 in table 1) after he hit the ground.



1 - Jockey mounted on horse in normal position approching a fence.

2 - Jockey is thrown forward as the horse clears the fence but lands with too sharp an angle.

3 - Jockey continues to fall forwards as the rear of the horse kicks upwards.

4 - Jockey begins to slide forwards down the horse's neck.

5 - Continuation of the falling with the jockey's body becoming more outstretched. At this point the jockey is clear of the horse.

6 - The jockey's head impacts with the ground and the head 'sticks' in this position.

7 - The jockey's body begins to rotate his head, with the neck acting as a pivot. His head is rapidly being pushed forward.

8 - The jockey's body squashes together under the momentum of the impact. The jockey is sliding along the ground on his head.

9 - The jockey's body continues to travel forwards about the stationary head.

10 - The jockey's body continues to go forwards.

11 - The jockey's body impacts with the ground.

12 - The jockey begins to sit up after a brief spell lying on the ground.

Fig. 5. Jockey #26 positions in a steeplechase fall. Frames every 0.04 s.

He fell freely, out of contact with the horse, from a height of 2 metres, and his forward speed when he hit the ground was 17 m/s. He slid for 3 metres along the grass face-down, then his head went forward suddenly(so that his chin touched his sternum) and his body somersaulted. There was no significant crushing of the liner. Jockey # 9 fell with a sideways rotation of his body after he hit the ground, so that the left side of his head struck the track. There was severe crushing of the left side of the liner foam of his Euro cap.

Table 1. Skull cap damage and jockey injury

No.	Manufac	type	liner damage				shell damage site	concussion severity
			site o/c	centre,mm above rim	severity	nose		
0	C	GRP	none					
1*	O	GRP	none				1 o/c low	
2	C	GRP	none				front	
3*	C	GRP	4 , web	30(+60),	severe		right	severe
4	C	GRP		rear webs	minor			
5*	C	GRP	8	rim(+60)	moderat		left	mild
6*	C	GRP	11?	30(+35)	minor		high left	moderat
7	C	GRP	none					none
8	E	GRP	none					moderat
9*	C	Euro	9	50	severe	yes	left ear	severe
10*	C	GRP	6	20(+ 35)	severe		rear	
11*	C	GRP	12	rim(+ 40)	moderat		front, left	
12*	C	Euro	6 & 12	rim	minor	yes		
13	C	Euro	3	rim	minor			severe
14	C	Euro	none			yes		moderat
15	C	Euro	none				scuff 10 o/c	
16	C	Euro	11:30	rim,	minor		grass 10 o/c	
17*	C	Euro	10	40			abras 10 o/c	moderat
			4	80	severe			
18*	C	Euro	11	60	minor			
19	O	GRP	9	rim(+35)	minor			
20	C	Euro	6	rim	minor	yes	rear	
21	O	GRP	11	web	minor			severe
22	O	GRP	12	rim(+35)	minor			moderat
23	C	GRP	none	(below)	minor		right ear	mild
24	C	GRP	LDPE	foam				severe
25	C	GRP	8	rim(+60)	severe			mild
26	C	Euro	none					
27	C	Euro	1	90	minor			
28	C	Euro	2	30	severe	yes	kick 2 o/c	
29	C	Euro	12.30	rim inside	moderat			mild
30	C	Euro	3	25	moderat			mild
31	C	Euro	9	135	severe		kick 9 o/c	moderat
32	C	Euro	11	rim inside	moderat			severe
33	C	Euro	2	135	minor	yes		minor
34	C	Euro	1	rim	minor	yes		bruised
35	C	Euro	11:30	rim	moderat			severe

* re- impacted later, 'web' means that one or more webbing supports for the cradle indented the liner inner surface. Locations by clock face, viewing cap from above, so 3 o/c is right side. C Champion, E Everoak, O Owen.

An impact near the shell rim of GRP cap #23, caused very minor damage to the foam liner, which ends 35 mm above the impact site. GRP cap #24 had been modified by the Jockey fitting low density polyethylene(LDPE) foam (in place of a cork layer?); this foam does not record indentations. Cap #20 was kicked upwards at the rear rim, cracking the ABS and causing the two rear leather nape straps to fail. This kick may have contacted the rear of the jockey's skull. There was kick damage on two other caps. In 7 of the 19 new-design caps(see column 6 in table 1) there was a central indentation on the inner surface of the liner brow, indicating that the front of the cap had been pushed down on to the bridge of the jockey's nose. Such damage cannot occur with the soft headband in the old-style caps. For Euro caps #29 and 32 the jockey's forehead has indented the inside of the liner while the exterior shape of the liner is unchanged.

Frontal impact sites are the most common (table 2), with rear impacts being the least common .'Front' includes 11 o/c and 1 o/c sites, 'left' includes 2 o/c and 4 o/c sites. In 17% of falls there is no evident impact site.

Table 2 Statistics of the impact locations for 35 caps

site	front	left	right	rear	none
old type	6	3	3	1	3
Euro	8	2	5	1	3
% of total	40	14	22	6	17

The height of the centre of the impact site above the lower edge of the liner is given in table 1 (with the extra height of the liner lower edge above the cap rim given in brackets for the old design, so that the figures can be compared). Low down impacts can be missed for the older designs, since the soft headband foam does not record impacts, and shell damage in this area may be from glancing blows. Therefore the height of the centre of the impact from the rim of the helmet was only classified for the Euro designs in table 3, which shows that low impact sites are more frequent than the higher sites impacted in BS 4472 and in the proposed European standard. Given the limited liner coverage in the old design (figure 1), it is clear that the new Euro design provides increased protection in a significant number of falls. There are 16 caps where details of the liner damage and the concussion severity are known, but there is no correlation between the two severity indices. This suggests that factors other than the linear acceleration of the head play a part in concussion.

Table 3 Height of liner impact site centre above the rim of the Euro caps

site	rim to 25 mm	above 25 mm
number	9	7
%	56	44

SHELL DAMAGE GRP shells have more variable stiffness when undamaged than injection moulded ABS ones(table 4), because of the variation in GRP thickness and resin content from the pressure-bag moulding process. The GRP shells are initially 2 or 3 times stiffer than the ABS shells, but they are damaged at lower deformations by the formation of creases and delaminations, whereas ABS only forms whitened creases at high strains. The same variation in shell stiffness and damage mechanism occurs in thicker GRP and ABS motorcycle helmet shells[13]. The radii of curvature of the caps were:-

frontal site (centred 50 mm above the rim)	105 and 90 mm
crown site	130 and 90 mm
rear site (centred 50 mm above the rim)	120 and 90 mm

Typical thickness were 2.0 to 2.1 mm at the front and rear sites, and 2.8 to 3.0 mm at the crown site, for both ABS and GRP shells made by Champion. Table 4 compares the stiffness of the damaged site with the average stiffness of the same site in a number of undamaged shells of the same design.

Table 4 Localised bending stiffness of the cap shells

cap	shell type	site	undamaged stiffness N/mm	damaged stiffness N/mm
5	GRP	rear	350 to 580	137
9	ABS		120 to 190	35

RESIDUAL PERFORMANCE Prior to 1994 it was not uncommon for jockeys to ride again after a fall using the same cap. We tested the residual performance of 10 caps. Figure 6 shows the striker force-deflection trace for a BS4472 type impact at, or within 50 mm of, the fall damage site. The initial constant-force part of the curve is due to the acceleration of the cap towards the headform, and there is little force on the headform. The subsequent linear part of the trace is due to the crushing of the foam between the flat rigid striker and the nearly-spherical headform. An analysis [14], assuming that the foam has a constant compressive yield stress *Y*, predicts that the force *F* is given by

$$F = 2 \pi R Y x \tag{1}$$

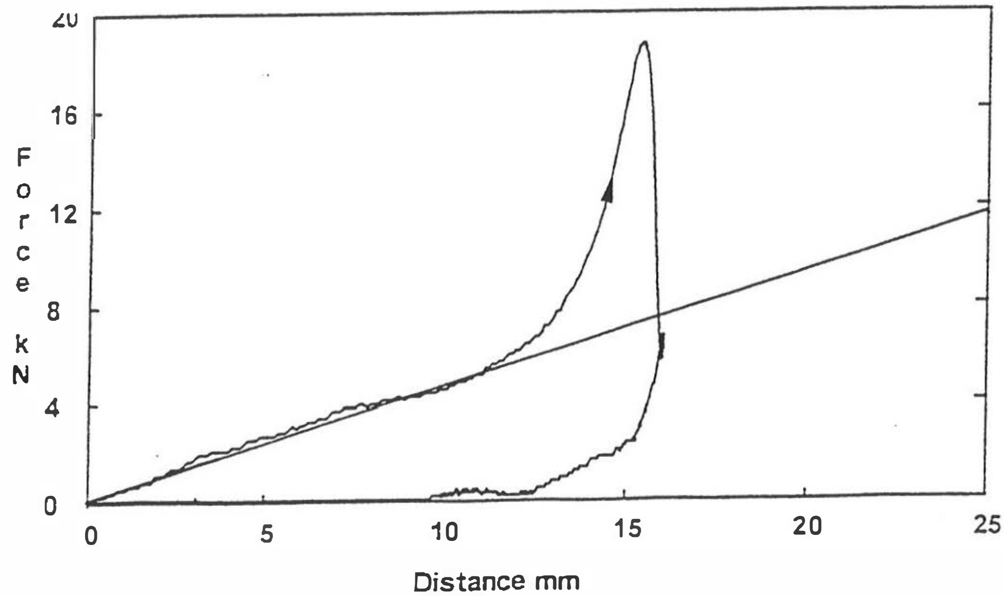
where *R* is the radius of curvature of the outer surface of the cap and *x* is the deflection of the foam in the centre of the impact patch. This approximation is obeyed by most soft-shell helmets when they impact a rigid flat surface. In figure 6a the linear part ends at a deflection of 12 mm, and the curve turns steeply upwards when the foam is compressed into a solid material. The polystyrene foam thickness at the impact site is about 14 mm, but there are a few mm of soft comfort foam, so the combination can be compressed by 16 mm. The foam thickness is inadequate for a 80 J impact on to a rigid flat surface, since the high 18.7 kN force would cause a serious brain injury. In contrast in figure 6b, the striker force never rises above 5 kN, corresponding

Table 5 Impact tests on the sites of the fall damage

cap no.	type	site	impact energy J	peak force kN	yield stress N mm^{-2}
1	GRP	crown	100	12.7	1.4 *
		front rim	80	**18.7**	0.8
3	GRP	rear right	80	10.2	1.5 *
5	GRP	crown	100	12.8	1.7 *
		left ear	80	**22.1**	0.3
6	GRP	top left	100	10.4	1.3 *
9	Euro	left ear	80	6.4	0.9
17	Euro	right rear	80	4.5	0.4
18	Euro	front	80	5.6	0.5

to a peak acceleration of 100 g. This is because the 20 mm thick polystyrene foam at the impact site is not fully crushed. Table 5 shows that the older design of cap produces much higher peak forces at the sites impacted than the new Euro design. **Results in Bold** would be failures or near failures if these sites were tested in BS 4472 (they are not). Apart from caps 1 and 5, the caps would still pass the standard , but the impact energy needed to cause a 12.5 kN force on the striker is far greater for the new Euro design than it is for the old 'Professional' design. The yield stress values in table 5 are calculated from the loading curve slope, equation (1) and an assumed shell radius of curvature R=100 mm. The starred values are much greater than the yield stress of the liner (see the next section), showing that the GRP shells contribute significantly to the response. The unstarred values for the Euro caps show that the low bending-stiffness ABS shells contribute little to the overall response.

a)



b)

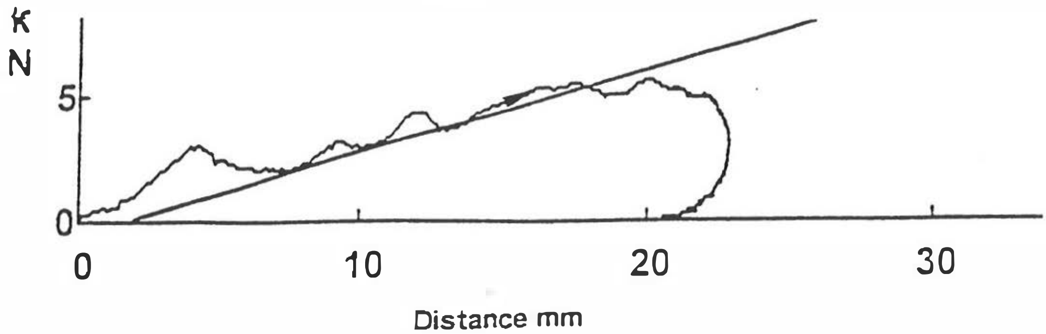


Figure 6. Striker force versus cap deflection for a flat steel striker hitting the damaged site on the cap while it is supported on a rigid headform. a) Owen GRP #1 at the front right site and b) Champion Euro #18 at a frontal site, 80 mm above the rim.

ANALYSIS OF LINER DAMAGE Polystyrene foam records impact deformation, recovering partially during the unloading stage of the impact, but not changing dimension thereafter. The foam liners are all moulded from pentane-containing beads, pre-expanded with steam. The foam density was 59 ±5 kg m^{-3} for all caps, bar cap 1 which had foam of density 82 kg m^{-3}. The compressive impact properties of a range of this foam has been investigated[14] so the initial yield stress Y = 0.8 N mm^{-2} of the cap foam can be predicted from the density. Figure 7 shows the relationship between the maximum strain in laboratory compressive impacts and the residual strain after the impact, for polystyrene foam of density 70 kg m^{-3}.

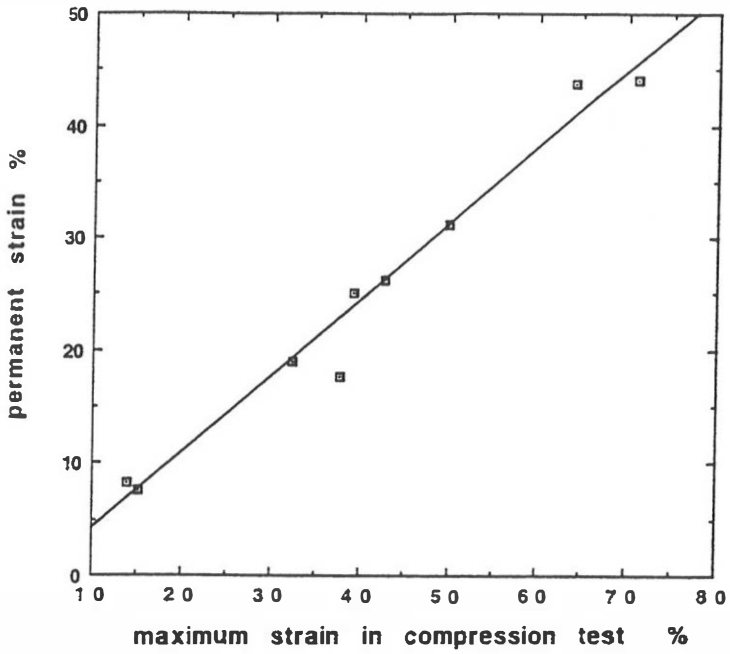


Figure 7 Maximum strain in laboratory compressive impacts versus residual strain after the impact, for polystyrene foam of density 70 kg m^{-3}.

Since the maximum residual strains in the cap liners were rarely greater than 20% the peak strains in the impact will be less than 40 %, and the foam can be treated as having a constant compressive yield stress Y. The area A of liner crushing is multiplied by Y to estimate the maximum impact force F_{max}.on the head This assumes that cap rotation during the impact was insignificant, since we cannot distinguish when the various areas of foam were crushed. If the crushed area extends to the lower rim of the foam liner, only a lower limit to the force can be calculated, since the force transmitted through the unprotected head or through the soft headband of the GRP caps cannot be estimated. Table 6 gives the estimated head accelerations assuming a head mass of 5 kg. The maximum linear acceleration values are greater than or equal to 100 g for only 3 of the first 28 caps. For several GRP shelled caps, where the impact site is at or below the rim of the foam liner; the maximum head accelerations could be large. In 8 of 19 Euro helmets the liner crush is minor, and in 3 it is non-existent, indicating that the linear acceleration of the head may not be the only cause of concussion

Table 6 Estimated maximum forces on the damaged caps

cap no	shell type	impact site	maximum force kN	maximum linear acceleration g
3	GRP	4 o/c on rim	> 4.8	> 96
10	GRP	6 o/c on rim	> 1.9	>38
17	Euro	10 o/c above rim	5.0	100
25	GRP	8 o/c on rim	> 4.4	> 88

DISCUSSION

The riding style of jockeys is different from that of recreational riders, as are the risks encountered, so the design of jockey skull caps should be considered separately from that of other riding helmets. For 56% of the 19 Euro skull caps examined, the impact site overlaps the site of soft headband on the older cap design, showing that the new design provided improved protection. When there is a large area of crushing of the polystyrene foam (table 6) the estimated linear head accelerations are 100 g or above. When bicycle helmets were examined[10], only 2 of the 10 cases involved concussion. The estimated head accelerations for these cases were 108 and 179 g, so this limited data is consistent with the estimates here.

For 58% of the falls causing concussion with the new Euro cap, the liner crushing is minor or non-detectable. This shows that either:-

a) the foam liner has too high a yield stress

or b) concussion is not solely due to linear acceleration of the brain.

Videos of 8 falls indicate that there is significant rotational motion of the head in some but not all of the falls. The sequence in figure 5 shows that the jockey's head rotated forward by about 1 radian in less than 2 frames(0.08 s), so the angular velocity is greater than 12 radians/sec. It was impossible to calculate the angular acceleration of his head with any accuracy. The liner of this cap was undamaged. The analysis of helmet impacts on deformable panels[15] is relevant to jockey caps hitting deformable race tracks. As the yield stress of the polystyrene foam is 0.8 N mm^{-2}, and the projected area of the upper front of the head is about 20000 mm^2, a evenly-distributed force less than 16 kN will not crush the liner. Allowing for some unevenness of the force distribution, it is still possible for a force of 7.5 kN to act without damaging the liner. This force would cause a linear head acceleration of 150 g, probably causing concussion. Therefore it is not yet possible to choose between possibilities a) and b) above. The indentation resistance of the track needs to be recorded for each fall, to help resolve the issue

Most helmets are designed to pass the tests in standards, so, if the test criteria in the standards are not linked to the biomechanics of the most common types of falls, the helmet design may not minimise the number of injuries. The foam in the upper regions of the jockey skull caps has a high yield stress to pass the impact test in BS 4472, but it was never found to be fully crushed, so it could be of a lower density hence lower yield stress. The foam at the lower edges of the caps is not tested in BS 4472, since the impact sites are higher up. This foam was fully crushed in 4 cases showing that the lower edges of the cap need more protection - either through using thicker foam of the same 60 kg m^{-3} density, or by extending the liner downwards, partially covering the ear. Nevertheless initial data indicates that the new skull cap design has reduced the concussion rate for jockeys by the order of 30%.

The sliding of helmets along the ground is not addressed in BS 4472.

One video of a fall shows, for a jockey whose chest fell flat on to the track, that his helmet slid for several metres along the grass without any head rotation occurring. This may indicate that grass is a low friction surface. Nevertheless the nose indentations listed in table 1 show that the helmets do rotate forward on the head in oblique impacts onto grass - this rotation increases the protective coverage of the forehead.

British Standards Quality Assurance produced a Product Approval Specification (PAS) 015:1994 [16] to encourage the manufacture of improved helmet designs, since BS 4472 could not be modified during the development of the European standard. In its impact test a helmet-clad free headform falls onto a rigid flat steel anvil at a velocity of 5.9 m/s(5.4 m/s for lower sites). The headform mass is a function of its size, and the headform acceleration must not exceed 250 g. Although the PAS has more stringent impact tests than BS 4472, it is for recreational riders who face different risks to jockeys, especially falls onto roads or stony tracks. The impact test equipment in PAS 015 is similar to those in the final draft of the European standard prEN 1384 [17] for riding helmets, which will be voted on this summer, but some of impact sites are lower. Falls of recreational riders are not videoed, which means that the impact kinematics of damaged helmets are rarely known. The impact test methods in the standards may need to be reassessed if it is found that helmets that pass PAS 015 have minor liner damage in falls causing concussion.

CONCLUSIONS

The performance of the Champion Euro Deluxe skull cap appears to be superior to the older design, with better protection against impacts low down on the cap, which account for 56% of impacts on the Euro caps. Damage to the GRP shells of the older design was common. Repeat impact tests, on the same site as the fall damage, showed that it is likely that 80% of caps would still pass BS 4472. The fall damage was usually minor, with severe crushing of the liner occurring in only 20% of the 35 caps (but for several of the older design caps the impact point was on the headband). Some concussion cases occur with the new design with only minor damage to the foam liner. This either means that the foam density is too high in the upper regions of the cap, or that the concussion is due to rotational acceleration of the head. Videos of falls confirm the latter as a possibility.

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REFERENCES

1. BS 6473:1988 Protective hats for horse and pony riders, British Standards Institution, London.
2. Mills N.J. and Whitlock M.D., Performance of Horse-Riding Helmets in Frontal and Side Impacts, Injury, 1989, **20**, 189-192.
3. British Standard 4472:1988, Protective Skull Caps for Jockeys.
4 Foster JB, Leiguarda R, and Tilley J. Brain damage in national hunt jockeys, The Lancet, 1976, **1**, 981-983.

5. Press J.M. et al, The National Jockey Injury Study: An Analysis of Injuries to Professional Horse-Racing Jockeys, Clin. J. Sport Med., 1995, **5**, 236-240.
6. Hamilton M.G. and Tranmer B.I., Nervous System Injuries in Horseback-Riding Accidents, J. of Trauma, 1993, **34**, 227-232.
7. Jockey Club General Instructions: Medical services on racecourses, August 1994
8. DeBenedette V., For Jockeys, Injuries are not a Long Shot, Phys. and Sports Med., 1987, **15**, 237-245.
9. Report by the Stewards, 1994, The Jockey Club, 42 Portman Square, London, W1H 0EN, U.K.
10 Smith TA, Tees D, Thom DR and Hurt HH, Evaluation and replication of impact damage to bicycle helmets, Accid. Anal, and Prev. **26** (1994), 795-802.
11. Hunt H & Mills N J, The protection of horse riders in impacts with the ground, IRCOBI conf., Stockholm (1989),157-168.
12 Mills NJ & Gilchrist A, Response of helmets in rotational and direct impacts, NATO/ASI meeting on Crashworthiness of Transportation Systems, Troia, Portugal, July 1996,
13 Mills NJ & Gilchrist A, Motorcycle helmet shell optimisation, Proc 36th Conf, Assoc. for Adv. of Auto. Med., Portland, Oregon, (1992), 149-162.
14 Mills NJ, Impact properties, in *Physics of low density cellular solids*, Ed. Cunningham and Hilyard, Chapman and Hall, 1994.
15 Mills NJ & Gilchrist A, The effectiveness of foams in bicycle and motorcycle helmets, Accid. Anal. and Prev., **23**, 153-163, (1991).
16. Product Approval Specification (P.A.S.) 015:1994, Helmets for Equestrian Use, British Standards Institution.
17 European Committee for Standardization (C.E.N.), T.C. 158 Head Protection, prEN 1384, Helmets for Equestrian Activities, May 1996.