Design of a force acquisition system for high-energy short-duration impacts

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Abstract: This paper describes a novel force acquisition system capable of measuring the force profiles of high-energy short-duration impacts. This force acquisition system was used to test dynamically a cricket leg guard and to create a contour map of the peak transmitted forces across the garment's surface. The cricket leg guard was found to provide most protection in the central shin and knee regions, areas most likely to be impacted normally and so to receive the highest-energy impacts. The use of this system will enable a dynamic test procedure to be developed to mimic impact conditions encountered during a game, allowing optimization of cricket pad designs for specific impacts.

Keywords: cricket, force measurement, personal protection equipment

1 INTRODUCTION

Standards are used in order to compare product quality and to ensure customer protection. These standards may have international authority, e.g. the International Organization for Standardization (ISO), they may be created locally by a manufacturer, or they may be imposed to protect the traditions of a sport by a governing body such as the Fédération Internationale de Football Association (FIFA). Governing bodies are also becoming increasingly aware that they have an obligation to protect their athletes or players, and regulations regarding personal protection equipment and performance standards are being specified [**1–5**]. In games where a blow or impact occurs, allowable upper levels of force are often quoted; unfortunately these specifications generally do not relate to the dynamic levels found in game situations, which means that their integrity may be questioned under closer scrutiny. For example, a recommendation for an increase in the tested force level for the British Standards test for football shin guards was proposed by Ankrah and Mills [**6**] after closer inspection of that standard. This may not mean that the protection specified is inadequate but the premise for its level is unclear and it may place an unnecessary barrier to design invention.

In the majority of testing standards for personal protection equipment, force measurement is used as a means of comparison (benchmarking) between different pieces of equipment. The decision on whether a garment provides sufficient protection is based on the fact that the transmitted force is less than a certain value; prime examples of this are in the British Standards [**1**, **2**] for the testing of cricket leg guards. In the testing of the shin protection on cricket leg guards, a steel anvil 350 mm long with a curved surface of 25 mm diameter is used to replace the leg and is rigidly attached to a support frame (Fig. 1). A section 50 mm long in the centre is free from the rest of the anvil and is mounted on a force transducer. The pad is mounted on this set-up and impacted with a 2.5 kg hemispherical steel striker of 72 mm diameter, which is dropped on to the pad at up to 5.65 m/s. The maximum allowable transmitted force is 5 kN for the shin region and 6 kN for the knee region; measured values greater than these cause the pad to fail this test. The system currently used does provide a repeatable test method which gives consistent results.

Unfortunately this form of test is dissimilar to the conditions of impact experienced during a game situation where the pad will be impacted with a relatively light object moving very quickly, compared with the heavy mass moving slowly as in the test. This

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is an important factor as the strain rate dependence of polymer foams has previously been demonstrated. Mills [7] stated that the compressive yield stress of a rigid foam has a tendency to increase linearly with increasing logarithm of the strain rate in compression tests. Although the exact strain rates of the British Standards test and a cricket ball impact during a game are not known, comparison of the conditions, i.e. a 2.5 kg mass impacting at 5.65 m/s compared with a 163 g ball impacting at over 30 m/s, should indicate that differences will be found. By testing the cricket pads at a non-specific strain rate it is possible that the protection of any incorporated foams may not be comparable with the protection afforded under game conditions.

The aim here is to create a testing procedure for cricket leg guards which is more representative of the conditions experienced under a game situation. First, a novel concept for measuring the force in high-energy short-duration impacts is introduced. This new concept utilizes a quasi-freely suspended anvil to take force readings and avoids the problems encountered by other systems under this type of impact. Using this rig a testing protocol for cricket leg guards can be designed which will more accurately replicate the strain rates of the materials and the impact energies experienced under normal use, while still capturing accurate force data. This should ensure a more realistic indicator of cricket pad performance and the protection levels afforded to players, and provide a more accurate assessment of the forces experienced.

2 FORCE TRANSDUCERS

A force transducer may be defined as a sensor which can convert a forced input into a measurable output signal. Depending on the type of transducer, this output may be in various forms but most commonly an electrical signal output is achieved. The electrical signal can be the result of a change in the resistance such as in a strain-gauge-type force transducer, or the signal can be generated directly by the force, such as in a piezoelectric crystal transducer, which is widely used for dynamic force measurements [8]. Most commonly, the piezoelectric material used in these sensors is a form of quartz which has a high stiffness; this gives it a high natural frequency and makes this type of transducer suitable for dynamic tests.

There are two main issues with force transducer usage. First, it is important that the transducer is mounted rigidly since, if the mounting surface moves during the applied force, this movement is sensed by the force transducer and vibrations are introduced into the force signal. Second, it is important that the natural frequency of the system remains significantly higher than the frequency of the impact. As the impact frequency and system frequency approach one another, vibrations will be introduced into the force signal, making it less reliable.

The natural frequency ω_n of a system is dependent on the mass m and stiffness k, according to

$$\omega_n = \sqrt{\frac{k}{m}} \quad (1)$$

As the mass increases, the natural frequency decreases. The effects of vibration on a signal can be seen in Fig. 2. Figures 2(a) and (b) show two measured signals individually, but Figs 2(c) and (d) show the effects when these are measured together. The only difference is that the smaller 'noise' signal is half a period

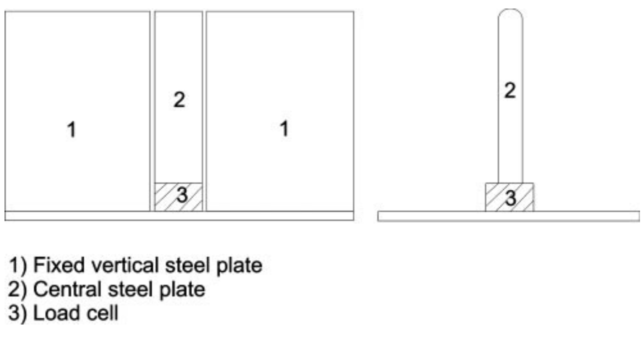

Fig. 1 Diagram of the anvil used in BS 6183-3:2000 for testing cricket leg guards

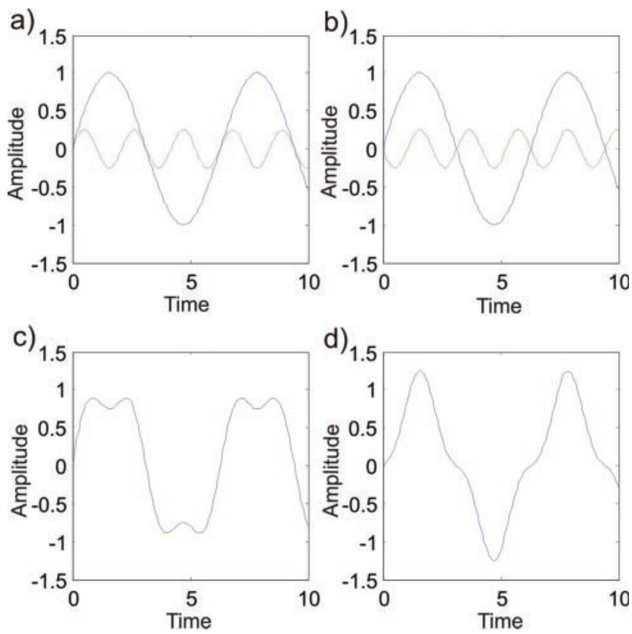

Fig. 2 Graphs of the amplitude plotted against the time, displaying the effects of high-frequency sine wave noise on a lower-frequency higher-amplitude sine wave

out of phase in Fig. 2(c). This leads to a significant difference in the measured signals, specifically if only peak values were given. Hence elimination of system vibration can be a significant factor in the accuracy obtained.

Force transducers have a wide variety of applications and, if used correctly, will give an accurate reading of the force applied. There are, however, certain situations where a significant mass may need to be attached to the force transducer and the impact will have a particularly short contact time. In this instance, the induced vibration in the system would make force transducer usage unviable and as such an alternative solution may be required.

3 ALTERNATIVE MEASURING SYSTEM

The most common method of measuring an applied force is to mount the impacted object rigidly and to apply the load. If the rigidity of the system is infinite or significant, then the measured loads will be accurate. Unfortunately, often system rigidity can be questioned and the assumption of an infinitely rigid system is also not representative of the human supporting the cricket pad.

It is possible to measure the force applied to an object by knowing its mass and the magnitude of any external forces on the mass, and by measuring the acceleration of its centre of mass. Newton's second law can then be used to find the resultant force. This principle has been applied to the development of a force acquisition system suitable for use during short-duration impacts.

Measuring the acceleration of the centre of mass of an object can be achieved in several ways:

(a) by mounting an accelerometer at the anvil's centre of mass;
(b) by drilling a hole to the mass centre so that a non-contacting device such as a laser vibrometer can be used to measure the acceleration of this point;
(c) by measuring the acceleration of points either side of the centre of mass and averaging this value (Fig. 3).

The linear and rotational accelerations in each direction and about each axis can then be found using the equations

$$a_x = \frac{a_5 + a_6}{2}, \quad r_x = \frac{a_3 - a_4}{2}$$
$$a_y = \frac{a_3 + a_4}{2}, \quad r_y = \frac{a_1 - a_2}{2}$$
$$a_z = \frac{a_1 + a_2}{2}, \quad r_z = \frac{a_5 - a_6}{2} \qquad (2)$$

These equations are only valid for small angles of rotation and if the pairs of linear accelerometers are

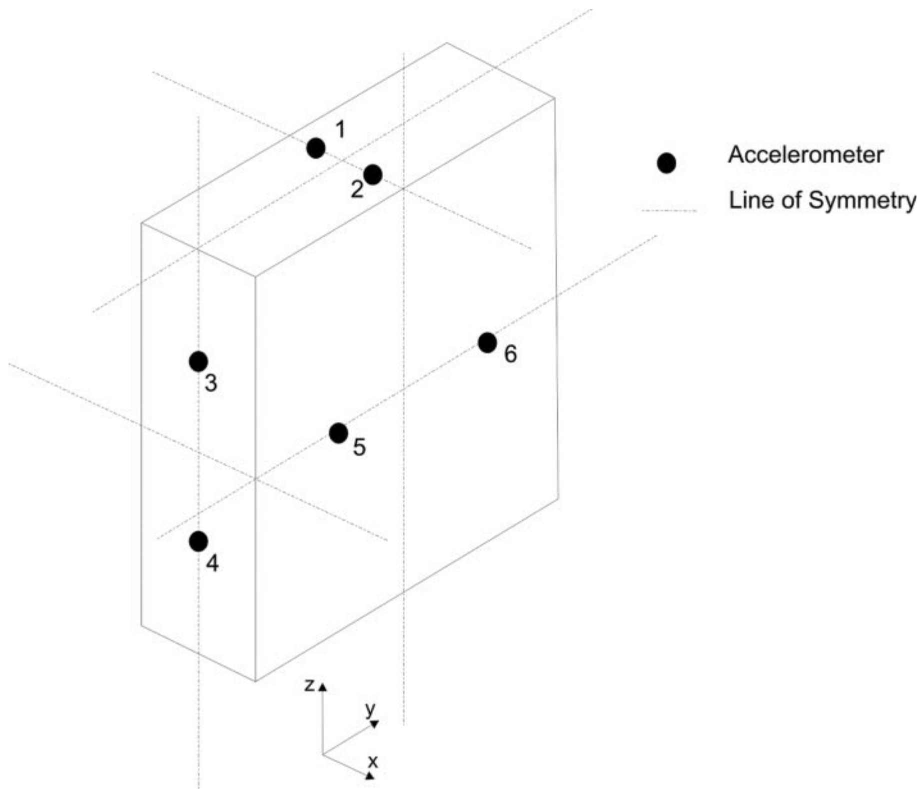

Fig. 3 Illustration showing how the acceleration of a mass can be measured using six accelerometers

positioned equidistant either side of the axis of symmetry.

The mass can be effectively freely suspended by using light springs or bungees and attaching it to an external frame. This requires aligning the bungee attachments at right angles to the impact direction so that the anvil mass becomes quasi-freely suspended. As shown in equation (1), the stiffness and mass of the system affect its natural frequency but, in this system, all the bungees are pulling at right angles to the force applied from the impactor (Fig. 4), and the stiffness becomes

$$k = k_{\text{bungee}} \cos 90^{\circ} = k_{\text{bungee}} \times 0 = 0 \quad (3)$$

Therefore, at the point of impact, the stiffness of the system is independent of the mass and tends to zero, and so the natural frequency will also tend to zero. This means that there will be no extra oscillations caused by vibration related to the natural frequency of the system, leading to a very 'clean' force profile even at short contact times.

The natural frequency of the force transducer does not need to be considered through the use of this method but the anvil itself still has a natural frequency which could be excited. Struck in the centre, a freely suspended rod can begin to oscillate about this point, which is depicted in Fig. 5. The natural frequency of a rod when struck was given by Bayon *et al.* [**9**] as

$$f_{\text{n}} = \frac{1}{2l}\sqrt{\frac{E}{\rho}} \quad (4)$$

These oscillations can be avoided through careful anvil design, and avoiding long thin shapes will keep the first natural frequency high. It is also possible to calculate this value and to compare it with the expected contact time to ensure that it is sufficiently high so that these frequencies are not excited.

Consideration of the stiffness of the bungees has less importance. At the point of impact the bungees are perpendicular to the applied force from the impactor; therefore, the rig has a little stiffness. For impacts with a long contact time the anvil and impactor will travel while in contact with each other. This will stretch the bungees and cause a retarding force vector to be applied to the anvil. The contact time can be increased if a large amount of deformation occurs, or if the impactor mass is not considerably less than that of the anvil. Having the mass of the anvil considerably greater than that of the impacting object is an important requirement of the system as it also ensures clean separation of the two objects, leading to a clearer measured force profile. Estimates for contact time can be calculated by considering a rigid body collision of two free bodies. The braking effects of the bungees on the anvil throughout longer-duration impacts can be calculated by simply resolving the forces applied by the bungees to find the magnitude of the retarding force on the anvil throughout the impact. Any objects attached to the anvil of significant mass, e.g. a cricket leg guard, are included in the system mass used to calculate the force.

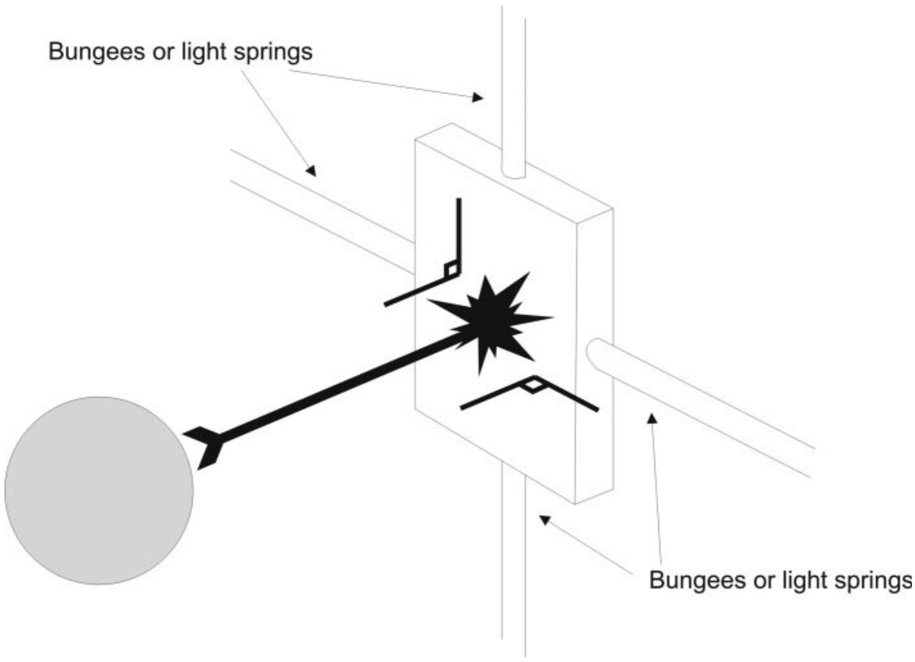

Fig. 4 Illustration showing the impact direction perpendicular to the force of the bungees

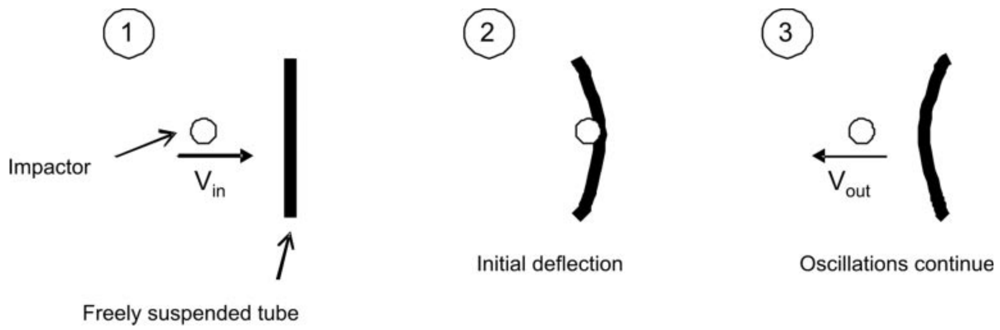

Fig. 5 Illustration of excitation of the first natural frequency of a slender anvil

4 PAD TESTING

Using this system it is now possible to design a representative test for cricket leg guards. The aim of the test is to represent the properties of the impact of a cricket ball on a leg guard worn by a player. The cricket leg guard selected represented a top-of-the-range pad, in terms of features and price. The pad also has a traditional look, with a vertically ridged surface on the shin region, horizontal knee rolls, and thigh protection. The pad can be seen in Fig. 6. Its construction utilizes a variety of materials to maximize the protection afforded; in the main shin area for example, several layers of foam are used together with rigid canes which help to spread the load up and down the leg guard. By spreading the load over a greater area the forces can be dissipated more easily. In the knee area, wool stuffing is used to provide the protection but there are no rigid structures incorporated to allow movement about the knee joint.

Having a low-speed heavy-impact test with corresponding failure criteria, such as the British Standards test, can lead designers to build in unnecessary features simply to pass such a test. Studies looking at rate of injury and their accompanying mechanisms in the literature do not report the major incidence of lower-leg injuries due to impacts. Mostly lower-leg injuries are reported as a category to themselves, without differentiating between sprains and strain injuries caused by running and the impact injuries being investigated here. The only paper to mention this distinction is by Stretch [**10**]; he discussed the fact that the majority of upper-limb injuries are due to ball impacts which cause fractures and/or joint injuries whereas the majority of lower-limb injuries tend to be muscle sprains and no reference was made to ball impacts. This suggests that protection afforded by leg guards tested under British Standards are adequate but the reasons for the tested energy levels and allowable transmitted forces are still unclear. In a realistic test the values can be based on data from the game and transmitted forces from the literature on injury mechanisms and thresholds. This higher-speed test represents the conditions experienced in a game more closely, which allows the personal protection equipment to be optimized fully for the conditions under which it will be used.

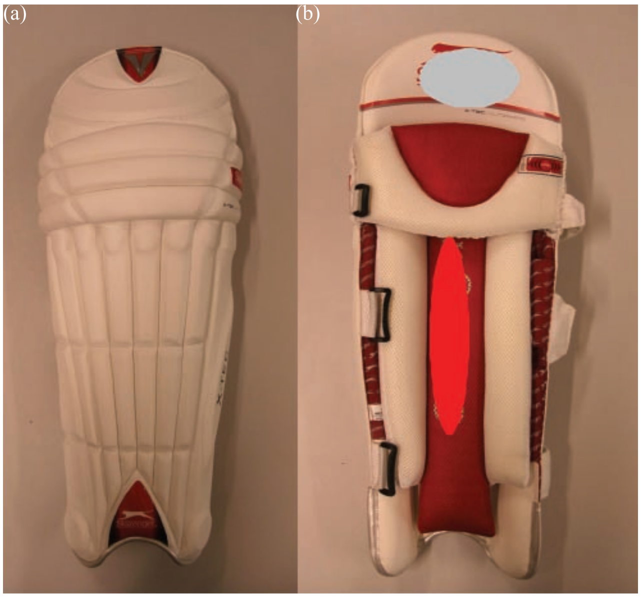

Fig. 6 Photographs showing the tested cricket pad from (a) the front and (b) the underside

The speed of the impactor will be achieved by using a custom-made pneumatic air cannon which can be pressurized up to 10 kgf/cm^3 and is capable of firing a ball at a speed in excess of 45 m/s (100 mile/h). The impactor to be fired will be a hockey ball, which has the same 163 g mass and diameter as a cricket ball, but no seam. This will enable repeatable firing speeds from the cannon as it will fit the barrel more exactly. The stiffness of a hockey ball is higher than that of a cricket ball, 115 kN/m under Instron compression testing for the hockey ball measured for a compression from 0 mm to 3.5 mm, whereas the cricket ball varies from the same initial stiffness up to 1 kN/mm stiffness at a compression of 3.5 mm. Both should act as rigid bodies when compared with the stiffness of a cricket leg guard.

The anvil in the rig serves several purposes. It mimics the shape of a player's leg, it is an attachment point for the cricket pad, and it replicates the leg mass to be accelerated. It is also important that the mass of the anvil is much greater than the mass of the impactor. This allows the two masses to separate quickly after impact as the lighter impactor effectively rebounds off the significantly larger anvil.

The design for the anvil utilized a simple cylinder of diameter 100 mm and length 130 mm. The dimensions were based on the dimensions of a player's leg, and also to allow attachment of the cricket leg guards. A fifth-percentile UK male calf radius is 51.2 mm, and 95th-percentile radius is 70.0 mm [**11**]; these measurements are taken at the widest portion of the calf and so the majority of the lower leg is smaller than this. When strapped to the anvil, the leg guard will have a similar radius of curvature to when it is attached to a human leg; this creates the initial static strain in the pad prior to impact which it would be under on a player's leg. The anvil is not attempting to mimic a leg except in its dimensions; it gives a rigid surface from which meaningful force data can be taken. The anvil was constructed from a single piece of steel to maximize its stiffness and to avoid any vibrations. Initial calculations estimated the natural frequency at over 2 kHz, or a period of under 0.5 ms. The anvil had a mass of 8.17 kg; this was the lightest that the anvil could be made, given the dimensions and available materials. This made it sufficiently heavier than the 163 g hockey ball to allow a short impact duration but also light enough that the bungee system could still support it.

The optimum design would have the force applied from the bungees coincident with the anvil's centre of mass. Because of the design of the cricket pad being tested, and the requirement of testing positions over its entire outer surface, the pad would need to be rotated around the anvil to allow impact with edge positions. Figure 7(a) shows the problem that this can cause if the bungee runs through the centre of mass; the amount that the pad can rotate is limited and the edges cannot be impacted. This was solved by running the horizontal bungee through an eyelet off the back of the anvil; the attachment points on the external frame were offset the same distance so that the bungees were still perpendicular to the impact direction (Fig. 7(b)).

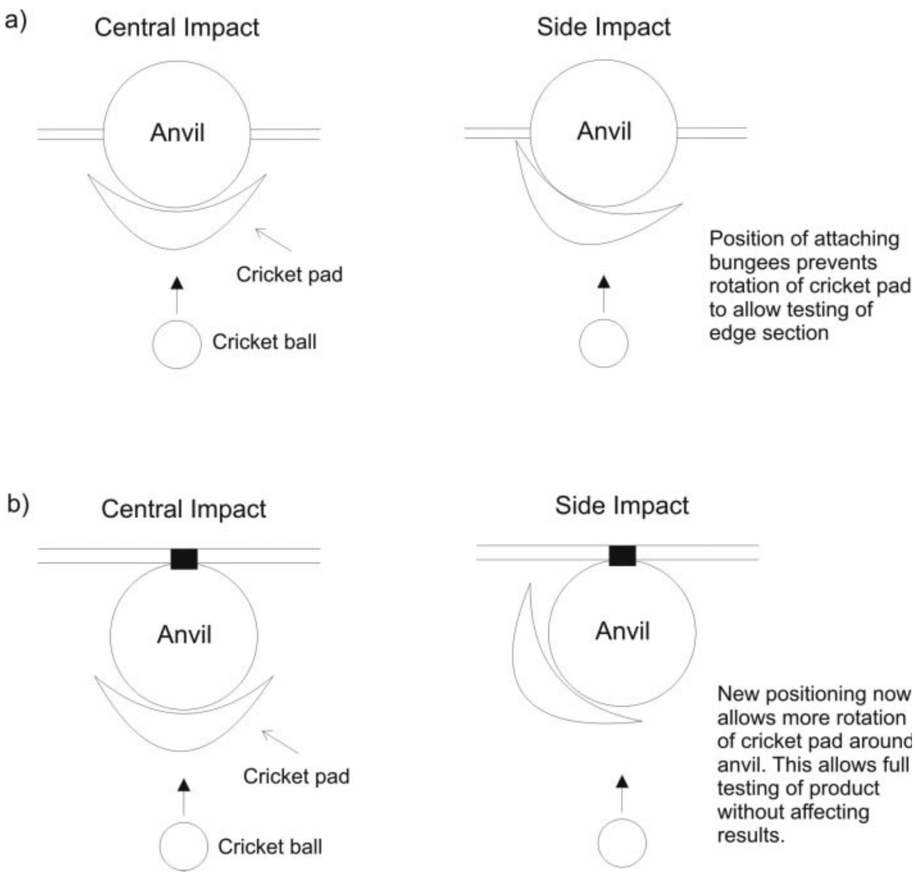

Fig. 7 Diagrams detailing a top-down view of (a) the ideal anvil and (b) the altered anvil showing the ability to deal with edge impacts

The accelerometers used were Bruel & Kjaer model 4375-V; they are recommended for use in shock and vibration analysis and have an operational frequency of between 0.1 Hz and 16 500 Hz. The accelerometers were recessed into the anvil to protect them from rebound impacts; six were used mounted in pairs equidistant from each of the centroid axes as in Fig. 2 earlier. Linear accelerations were then found by averaging the readings from each pair. Figure 8 shows the final anvil design; the cut-out sections for the accelerometers can be seen on the top, side, and back of the anvil. Matching cut-outs were made on the bottom of the anvil to maintain the mass centre close to the geometric centre. Similarly, cut-outs were made on both sides of the anvil, despite the fact that the accelerometers are positioned on only one side. Sections of material were also removed from the front of the anvil to balance the loss of material from the rear; to maintain a smooth curve for impacting, the material from the front was removed from the top and bottom of the anvil's front surface. The accelerometers were then connected to two Bruel & Kjaer charge-conditioning amplifiers. The data were then analysed using an M + P International SO analyser using Smart Office software. Data were sampled at 25.6 kHz for a period of 0.32 s; a 10 per cent block pretrigger was used to ensure that all data were captured consistently.

The bungees used to suspend the anvil had a diameter of 16 mm and their stiffnesses are inversely proportional to their lengths. When tested on a material testing machine at 100 mm/min, they were found to be relatively linear beyond a strain of 20 per cent. The calculated linear stiffness of a metre length of the bungee used was 114.98 N/m. These bungees attached the anvil to a custom-built frame within the protective enclosure of the air cannon under a strain of 20 per cent to utilize the linear portion of their stiffnesses. The ends of the bungees were put through attachment loops on the anvil and their ends crimped; a similar method was used to attach the bungees to the external frame. To evaluate the leg guards, preliminary testing showed the displacement of the anvil to be negligible. This results in minimal retarding force applied by the bungees; therefore no resolution of forces is required to account for this error.

16 suitable impact positions were identified across the surface of the cricket pad (Fig. 8). Each of these was impacted three times at 31 m/s (70 mile/h) normal to the pad's surface, and the accelerations were measured in the three axis directions. A speed of 31 m/s was selected to simulate the release speeds of bowlers of up to 35 m/s (80 mile/h), based on work on the release speeds of elite bowlers by Abernethy [**12**] and taking into account the 14.3 per cent loss in speed of contact with the playing surface as reported

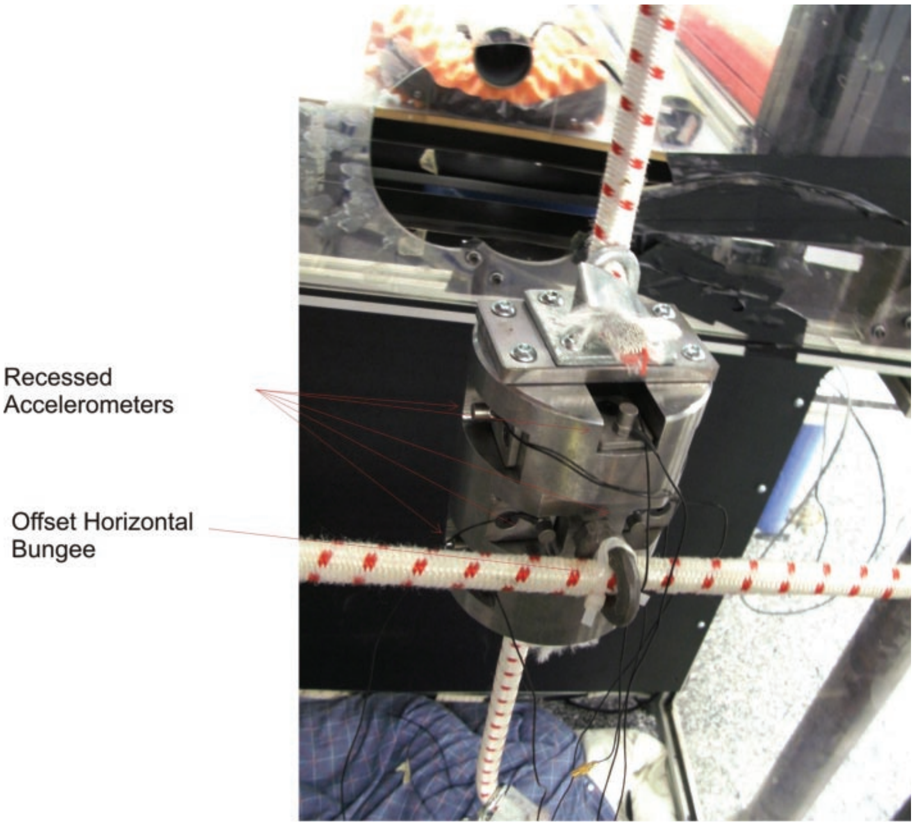

Fig. 8 Photograph of the final anvil attached to the bungee system

by Penrose *et al.* [**13**]. The time between repeated impacts, although not measured directly, was kept consistently around 3 min owing to the time required to reset the measuring equipment. This time period has been observed to be representative of the time lapse between successive balls during a standard over of cricket with various bowlers taking between 1.5 and 3.5 min between balls. This test will therefore represent a worst-case scenario of three successive balls contacting the pad in the same area. MATLAB was used to collate the acceleration data and to sum the vectors to give a magnitude and direction to the maximum acceleration; the applied forces for each impact were calculated using input mass data. The peak force value was then found for each set of three impacts and the mean taken to give an average peak force value at each location.

5 RESULTS

Figure 9(a) shows the 16 impact locations across the surface of the cricket pad. These points were selected to give a representation of the variation in protection across the whole of the leg guard surface, but also to highlight differences in protection between specific areas. The mean force of the three peak readings at each position is shown as a force contour plot in Fig. 9(b). The results of each impact are shown in Table 1, together with the range of these values. These are the total resultant force values; the resultant direction was always close to the impact direction but pad surface contours and variations in padding thickness could affect this. Of all 38 readings, only one was considered anomalous and removed. This particular reading occurred at position 7.

The lowest peak force values measured were at positions 9 and 11, with the average peak transmitted force at these positions being 5232 N and 4609 N respectively. The highest readings of over 10 kN were recorded around the ankle protection of positions 1 and 3. The next highest peak forces were measured on the thigh protection of positions 14, 15, and 16. These mean peak force values are shown in Table 1 together with the ranges of the readings.

6 DISCUSSION

Assuming that a lower transmitted peak force value is representative of a higher degree of protection, it is

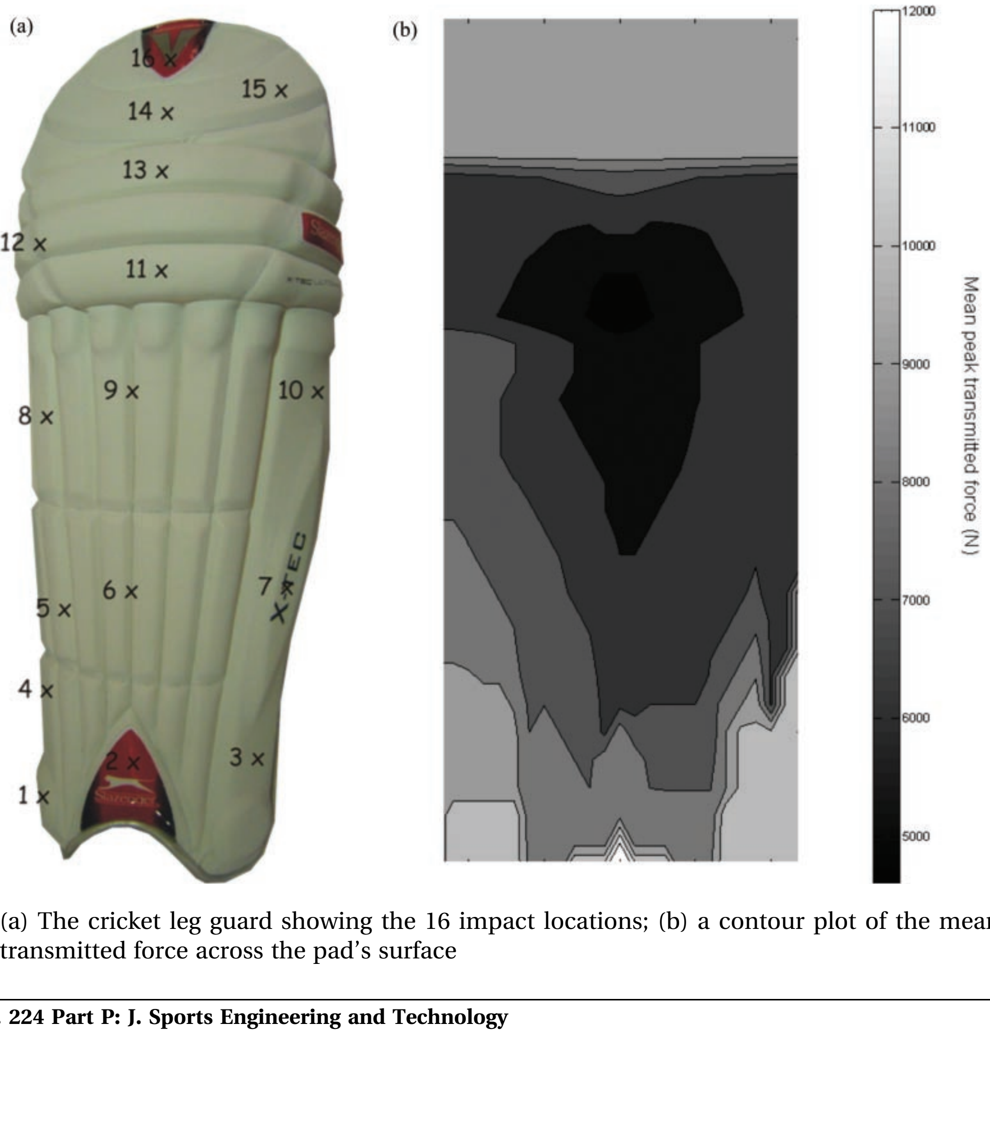

Fig. 9 (a) The cricket leg guard showing the 16 impact locations; (b) a contour plot of the mean peak transmitted force across the pad's surface

Table 1 Resultant mean peak forces and ranges for the 16 impact positions

Position	Peak force (N) for the following impacts			Mean peak force (N)	Range (N)
	Impact 1	Impact 2	Impact 3		
1	10 204	10 943	11 077	10 741	873
2	7 646	8 325	9 848	8 606	2 202
3	10 157	9 936	10 572	10 222	636
4	8 951	9 211	9 701	9 288	751
5	8 025	8 407	7 064	7 832	1 343
6	5 911	5 983	6 688	6 194	778
7	5 533*	7 307	7 762	7 535	456
8	6 715	8 065	7 852	7 544	1 349
9	4 515	5 930	5 250	5 232	1 414
10	7 182	6 928	6 456	6 855	726
11	3 469	4 675	5 684	4 609	2 215
12	5 438	6 868	7 141	6 483	1 703
13	5 814	7 125	9 439	7 459	3 625
14	10 211	10 304	9 754	10 090	550
15	10 521	10 065	8 968	9 851	1 553
16	9 425	10 201	10 287	9 971	862
Mean	7 612	8 142	8 346		

*Anomalous result.

clear that various levels of protection are afforded across the surface of the leg guard (Fig. 9). The highest amount of protection is provided on the central shin region and on the knee roll. These are the areas where normal impacts would be most likely to occur. As the batter moves his leg towards the line of the ball to play a shot, it is these central regions which line up with the ball's trajectory. Impacts to outer regions will tend to be oblique impacts as these areas curve around the sides of the leg and are not aligned with the ball's flight. There is also more protection on the outside of the shin than on the inside, as it is the outside of the shin which is closer to oncoming balls.

A general trend across the three impacts at a single site was for the peak force value to increase. This may have occurred as the materials did not fully recover from the previous impact or where the leg guard became permanently damaged. This may require further investigation but, as the time period between impacts is representative of the time between balls in a match, these results remain valid. This is also displayed in the range of the results. Positions 11, 12, and 13, together with position 2, show the highest variation between the three readings and also coincide with the use of wool stuffing as the main padding material instead of the foam-based materials which form the majority of the padding elsewhere.

Of significant importance in demonstrating the efficacy of this testing method is the clarity of the force trace. The three impacts at position 6 are shown overlaid in Fig. 10. This shows the raw unfiltered data multiplied by the constant value for the mass to give a force signal. There is minimal noise and disruption to the signal despite the high peak forces and low impact time. This figure also makes the effect of

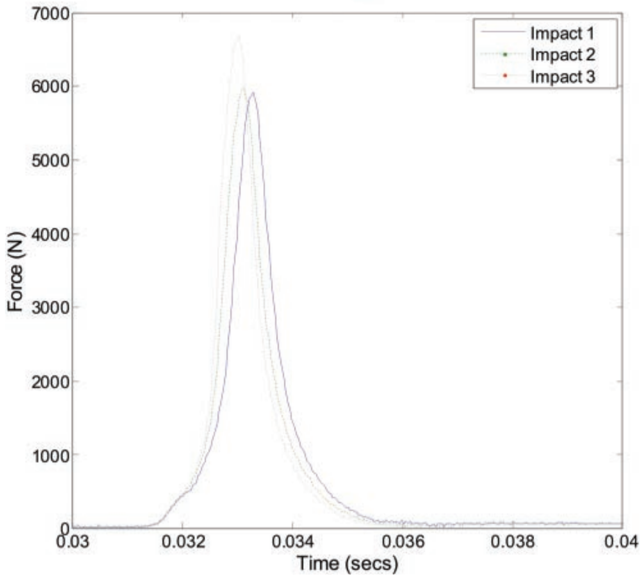

Fig. 10 Graph showing force–time data for the three separate impacts at position 6

multiple impacts clear. Each consecutive impact has a steeper gradient and reaches its peak force sooner during the impact; it also climbs to a higher peak force value. As discussed previously, this is likely to be a result of the material behaviour to repeated impact.

Within the time frame of this impact, the distance travelled by the anvil is less than 1 mm. Therefore the breaking forces exerted by the bungee can be neglected.

There are limitations to this method. The accelerometers are set up to measure the acceleration of the anvil's centre of mass; however, once a pad is attached to the front of the anvil, this position moves. During the impact, the ball also becomes part of the system, and the centre of mass moves again. Throughout the impact, the pad is compressing and, as such, the centre of mass is constantly moving its position within the anvil. The accelerometers are therefore only actually measuring the acceleration close to the centre of mass throughout the impact. The mass of the anvil is far greater than the mass of either the pad or the ball; therefore the additions of these two objects to the system should not move the centre of mass significantly. As the anvil is effectively rigid, any deformations will be small, particularly towards its core where the centre of mass is; this should mean that measuring the acceleration of a position close to the centre of mass will give the same reading as measuring the acceleration of the actual centre of mass and should not affect the accuracy of the results.

It is assumed that the contact time of a cricket ball on a leg guard attached to a player's leg would be longer than that measured using this experiment. On a cricketer's lower limb, apart from the central rigid area of bone, there is considerable soft tissue which can transfer energy away from the site of impact. Even the bony region will not be as rigid as the steel anvil used in this experiment. Both these factors will have the probable effects of increasing the contact time of the impact and decreasing the peak forces experienced by the player.

7 CONCLUSIONS

The current testing standards for cricket leg guards sets adequate levels of performance for the protection equipment without approaching the conditions experienced within a game situation. The use of a dynamic test similar to that presented within this paper would allow a higher level of optimization under a more representative situation.

This dynamic testing experiment has shown the difference in protection levels afforded by the different areas of the cricket leg guard, and in particular the difference in recovery rates of the materials which may or may not show up in other testing methodologies. It is possible that repeated impacts to a specific site on the pad could lead to a contusion. If this recovery rate difference were to be made clear in product tests, then it may lead more companies to use the more quickly recovering foam materials for players' safety.

If this dynamic testing procedure were to be utilized in the standardization of cricket leg guard protection, the highlighted weakness of the material recovery rates may lead to the use of an alternative failure criterion. A hits-to-failure criterion with a lower threshold force value to cease testing may be used to establish protection levels and to indicate a possible pad lifespan.

This dynamic testing process is possible because of the novel system of force measurement. This solution provides a suitable alternative to force-transducer-based measurement systems particularly where noise and vibration have become issues.

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NOTE

Since this paper was written, BS EN 13061:2001 [**3**] has been withdrawn and has been replaced by BS EN 13061:2009 [**14**].

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APPENDIX

Notation

a	linear acceleration (the subscript denotes direction or the accelerometer number) (m/s^2)
E	Young's modulus (Pa)
f	natural frequency (Hz)
k	stiffness (N/m)
l	length of the rod (m)
m	mass (kg)
r	rotational acceleration (the subscript denotes the axis of rotation or the accelerometer number) (rad/s^2)
ρ	density of the material (kg/m^3)
ω_n	natural frequency (rad/s)