

Performance of football shin guards for direct stud impacts

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Abstract

Football shin guards were evaluated against a kick from a studded boot. The bending stiffness of their shells, and their response when impacted by a stud, were assessed using finite element analysis (FEA) and determined experimentally. A test rig was constructed with the leg muscle simulated by flexible foam, with the force distribution along the tibia and to the lateral muscle measured using flexible force sensors. High-speed photography confirmed deformation mechanisms predicted by FEA. Load spreading from the stud impact site correlated with the guard shell bending stiffness. The best guards use shells of complex shape to increase their transverse bending stiffness.

Keywords: football, soccer, shin guard, bruising, protection, impact

Introduction

Association Football (soccer) leg injuries are common. Analysis of their prevention is, however, complex, involving engineering design, materials selection, and the biomechanics of motion and injuries. The International Football Federation (FIFA) requires that professional players wear shin guards during matches. The basic construction is a shell over a foam layer (Figure 1). They are worn under socks, protecting the front of the tibia and the lower leg muscle. The transverse (horizontal) bending stiffness of most guards is low to allow the sock tension to bend them to the leg shape. However, the transverse bending stiffness

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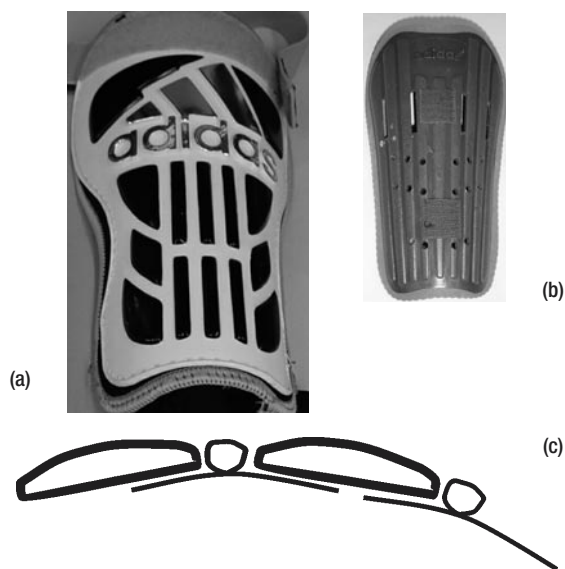


Figure 1 Some guards tested (a) Adidas Venom, (b) Adidas basic, (c) cross-section of Adidas segmented (the thin PE extrusions are sewn to cloth, the tubular PE mouldings are in pockets).

should be sufficient to transfer load from a central impact, away from the bone, to the muscles at the side of the tibia. The internal foam layer must be suffi-

ciently flexible to prevent discomfort or chafing, but resistant enough to act as an energy absorber.

European Standard

BSEN 13061 (2001) describes shin guards as being intended to significantly reduce the severity of laceration, contusion and skin puncture caused by impacts. By inference, they are not intended to prevent tibia fractures. Consequently guards are more likely to be effective against kicks from studded boots, than from a high-energy impact from another player's lower leg or foot. The impact tests are not demanding, and their impact energies are not justified in any way. In one test, a stud of diameter 10 mm, attached to a 1 kg mass, makes an almost-tangential (10°) impact at 5.4 m s^{-1} . The guard must not tear or perforate, but there is no force measurement. In a blunt impact test with a flat-faced, horizontal bar (mass 1 kg, width 14 mm, radius of corner 2 mm) with an extremely low 2 J kinetic energy, the peak force allowed is 2 kN.

Football leg injury biomechanics

Hawkins & Fuller (1999) found 20% of soccer injuries were contusions (bruises), and 13% occur to the lower leg. Boden (1998) reviewed leg injury studies, noting that the majority of 31 fractured legs from a direct blow, occurred while wearing shin guards. He could find no information on reductions in soft tissue injuries since shin guards became mandatory.

The criterion for bone fracture was found by loading cadaver tibias in bending at impact rates. They fractured at forces in the range 4 to 7 kN (Nyquist *et al.*, 1985), and at $2.9 \pm 0.4 \text{ kN}$ (Francisco *et al.*, 2000). If the foot is planted on the ground, and the opposing player's foot loads the tibia near its centre, the kinetic energy of the tackle exceeds the fracture energy of the tibia. Even if a shin guard could shunt loads to the knee and ankle, this would increase the risk of knee injuries, which are more difficult to treat.

The criterion for soft tissue contusions in humans is not established. Crisco *et al.* (1996) impacted the leg muscle of rats with a 6.4 mm diameter nylon hemisphere to cause contusions; the average pressure over the projected area of the hemisphere reached 9 MPa. Beiner & Jokl (2001) could not decide whether the muscle contusion criterion should involve force,

pressure or another mechanical variable. In this paper, it is assumed that the criterion for bruising the soft tissue of the ankle and lower leg involves the peak pressure. As a working hypothesis, contusions are expected if the order of magnitude of the pressure exceeds 1 MPa.

Leg anatomy and tibia stiffness

The tibia position is asymmetric in the human leg (Ellis *et al.*, 1994), with very little soft tissue cover on the medial surface and anterior border. Heiner & Brown (2001) describe the structural properties of a biofidelic artificial tibia, with a bending stiffness of 180 Nm^2 in the antero-posterior plane, equal to the mean stiffness of a number of cadaver tibias. This artificial tibia is produced by Sawbones (Pacific Research Labs, Vashon, CA, USA) using epoxy resin, reinforced with short E-glass fibre, around a foam core.

Previous shin guard test rigs

Although a test rig should simulate the leg and foot biomechanics, previous test rigs were simple, with few moving parts. A fixed wooden leg, with the grain running along the leg, was used by Philippens & Wismans (1989) and by Lees & Cooper (1995); however, it provides too-rigid a support for the sides of the guard. Bir *et al.* (1995) used the hinged lower leg of a Hybrid III car-crash dummy, which is not biomechanically realistic, as the central steel rod is covered with a thick, stiff, PVC plastisol skin which only has a cosmetic role. Further, they did not define adequately the frictional conditions between foot and the ground. In the Francisco *et al.* (2000) rig, rubber-covered foam (no details given) surrounded a Sawbones tibia, which was simply supported at both ends. The nearly-rigid striking objects used were either a 70 mm diameter hemisphere, representing a foot (Philippens, 1989 and Lees & Cooper, 1995) or a metal cylinder of radius 38 mm, with its axis at 90° to the leg, representing another player's leg (Bir *et al.*, 1995 and Francisco *et al.*, 2000). The latter used a 12.7 mm thick rubber cover on the cylinder.

None of the research considered stud impacts, nor did the test rigs simulate foot flexibility. The injury mechanism considered was tibia fracture. Bir *et al.* adjusted the striker kinetic energy (not quoted) to give

a peak force of 2.3 kN with the unguarded leg, and found that guards reduced the peak force by 40 to 70%. Phillipens & Wismans (1989), using a kinetic energy of 5.3 J, found guards reduced the peak force by 28 to 53%. However Francisco *et al.* (2000) found reductions of only 11 to 17%, for energies from 8 to 21 J. They were the only researchers to comment on shin guard designs, making the points that:

- a) fibreglass shells were better than other materials in distributing the impact force
- b) increasing the compliance (i.e. by using air bladders) attenuated peak forces
- c) increased foam thickness was more important than increased guard length.

Effective mass and effective impact energy

The test impact should produce a similar impact force–time trace, and similar pressure distribution on the guard, as that experienced in play. However the striker is usually a single mass rather than the connected bony masses and soft tissues of the foot. Some material properties may be rate dependent; if so, the impact velocity V should be typical of football impacts.

If the impact force has a single, short-duration peak, it is possible to model this as a collision between two masses. In this case, the test rig foot mass should be the *effective mass* M_e of the human foot, defined as the mass of an elastic body, with the same momentum as the real foot, which produces the same peak force in an impact. Mills & Zhang's (1989) analysis, of the impact between an elastic body of mass M_e and velocity V with a fixed body (of effectively infinite mass), gave the initial peak force as

$$F = V\sqrt{(M_e k)} \quad [1]$$

where k is contact stiffness (N m^{-1}) between the bodies. Consequently, if the force–time trace, measured for a kick to a footballer's leg, has a single peak with a peak force F , the value of M_e can be evaluated. At present, no one has instrumented a footballer's leg and recorded impact peak traces. However, if the impact force vs. time trace has a long duration with several peaks (as in the vertical component of the foot strike force in running) a more complex model is required, with several linked masses and springs.

It is easier to analyse a guard's force-deflection response if it is supported on a rigid anvil. However this tends to increase the impact severity, compared with a real-body impact. Gilchrist & Mills (1996) considered the effective striker kinetic energy in pre-1985 motorcycle helmet standards, to allow comparison with later standards where the helmet struck a fixed anvil. A striker, of mass m_1 and initial velocity V_1 , impacts a leg and guard of mass m_2 and initial velocity $V_2 = 0$. Assuming that the leg moves in a straight line after impact, momentum is conserved in the collision, so the common velocity V_c of the masses at the moment of nearest approach is:

$$V_c = \frac{m_1 V_1 + m_2 V_2}{m_1 + m_2} \quad [2]$$

The *effective impact energy* E_e is defined as the energy input to the guard up until the time when m_1 and m_2 have a common velocity (when there is peak guard deformation). Irrespective of the coefficient of restitution of the guard

$$E_e = \left(\frac{m_2}{m_1 + m_2} \right) \frac{m_1 V_1^2}{2} \quad [3]$$

For a fixed-leg test rig, the striker kinetic energy should be the *effective impact energy* of the football impact. Lees & Nolan (1998) quote peak toe velocities of 16 ms^{-1} in a placed-ball kick. The effective mass of the foot is smaller than its total mass, which can be seen from the following example. Clauser *et al.* (1969) give the foot mass as 1.5% of the total body mass, say 1.05 kg for a 70 kg player. Clarys & Marfell-Jones (1986) give the bony mass of the foot as 31% of the total, say 0.32 kg for the same player. However foot flexibility is considered in modelling footstrike forces (Giddings *et al.*, 2000), which reduces the effective mass. Hence, the effective mass of the forefoot bones may be $\approx 0.1 \text{ kg}$; for a 16 ms^{-1} kick velocity the kinetic energy is 13 J. If a forefoot strikes a lower leg bone of mass 0.62 kg, the effective kinetic energy by equation (3) is 11 J. Hence the target striker kinetic energy for testing would need to be around 10 J. Given the range of relative leg-to-leg relative velocities that occur in football impacts, this energy is only an order of magnitude estimate.

Direct vs. oblique impacts

Although oblique stud impacts are simulated in BSEN 13061, the research described here only considers direct impacts. The justification is similar to that in helmet standards; the direct component of the impact velocity is the main cause of the injury – in this case bruising due to excessive pressure – while the tangential velocity component only causes the guard to slide on the leg, and does not increase the pressure on the leg. If the guard shell is not penetrated, there is unlikely to be skin penetration. Consequently the performance of shin guards is considered as a function of the impact energy from the direct component of stud velocity.

Research aims

The aims of the research were therefore to:

- examine a range of shin guard designs, with regard to materials and design
- perform a FEA of their shells, to identify the features that provide bending stiffness, and to validate this by experiments
- perform FEA of a stud impact of a guard on leg, to predict deformation mechanisms and assess the contributions of the foam and shell to energy absorption
- use photography to confirm the deformation mechanisms
- construct a test rig with a biofidelic ‘muscle’ for force shunting from the bone; direct stud impacts with an effective energy input of about 10 J were used as the worst-case scenario
- find which guard absorbed the most energy before the local pressure reached a level that risked bruising.

Finite element modelling

Foams are non-linear materials, with rate dependent properties. The approach was to perform FEA using the approximation that the foam is a non-linear elastic (hyperelastic) material, and validate this experimentally. Large changes in foam and shell geometry, as the impact proceeds, are considered using ABAQUS standard version 6.2.

Foams modelled

Zotefoams EV30, crosslinked, closed-cell, ethylene vinyl acetate (EVA) copolymer foam of density 30 kg m^{-3} , was tested as a generic EVA foam. Impact compression tests at 20°C could be fitted with an equation for the compressive stress:

$$\sigma = \sigma_0 + \frac{p_0 \varepsilon}{1 - \varepsilon - R} \quad [4]$$

where ε is the strain, the initial yield stress $\sigma_0 = 32 \text{ kPa}$, and the effective cell gas pressure $p_0 = 69 \text{ kPa}$. When the foam density changes, there is little change in p_0 , but an increase in σ_0 . The majority of the compressive stress is due to the cell air content.

Rogers *Senflex 435* of density 76 kg m^{-3} was used in the test rig to simulate leg muscle. The 4 reflects the nominal density of 4 lb ft^{-3} , but the meaning of the 35 is not clear. These appear to be amorphous copolymers of ethylene with about 70% styrene (Ankrah, 2002), with parameters for equation [4] of $\sigma_0 = 192 \text{ kPa}$, $p_0 = 55 \text{ kPa}$.

Hyperfoam model

The foam uniaxial impact compressive response was fitted with parameters from Ogden's (1972) strain energy function for compressible hyperelastic solids:

$$U = \sum_{i=1}^N \frac{2\mu_i}{\alpha_i^2} \left[(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3) + \frac{1}{\beta_i} (\mathcal{J}^{\alpha_i \beta_i} - 1) \right] \quad [5]$$

where λ_i are the principal extension ratios, $\mathcal{J} = \lambda_1 \lambda_2 \lambda_3$ measures the total volume, the μ_i are shear moduli, N is an integer, and α_i and β_i curve-fitting non-integral exponents. The latter are related to Poisson's ratio ν_i by:

$$\beta_i = \frac{\nu_i}{1 - 2\nu_i} \quad [6]$$

The parameters of a $N = 1$ model were altered to fit the experimental data for EVA foam (Figure 2) using $\mu = 55 \text{ kPa}$, $\alpha = 0.5$, and $\nu = 0$. Although only four impacts are shown in Figure 2, Verdejo & Mills (2002) showed that thousands of impacts on EVA foam had little effect on the response.

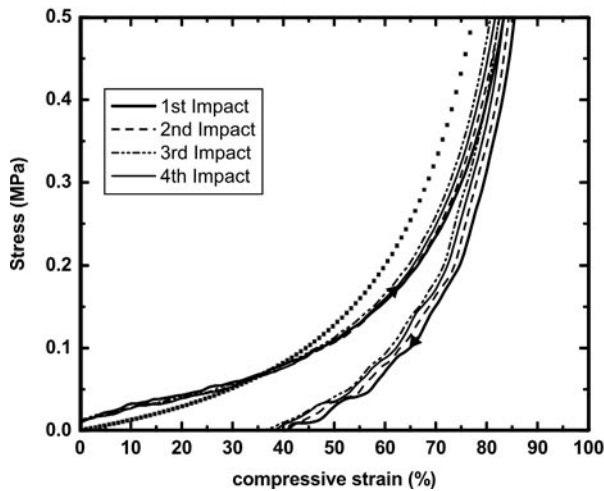


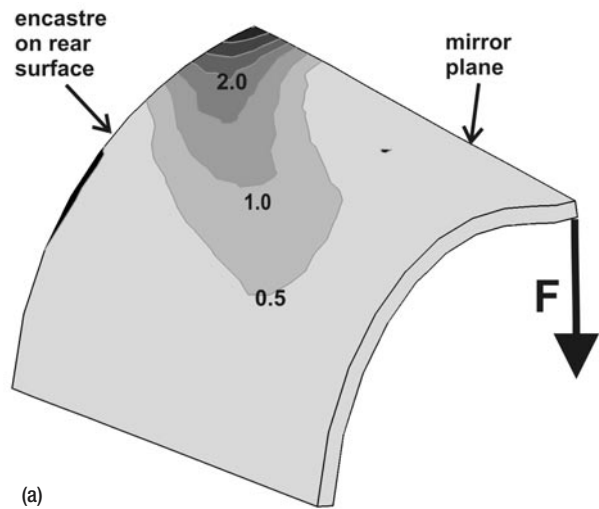
Figure 2 Impact compression stress-strain response for EVA foam of density 30 kg m^{-3} , for loading and unloading, repeated four times at short intervals, compared with hyperelastic model prediction.

Material parameters for shell and leg

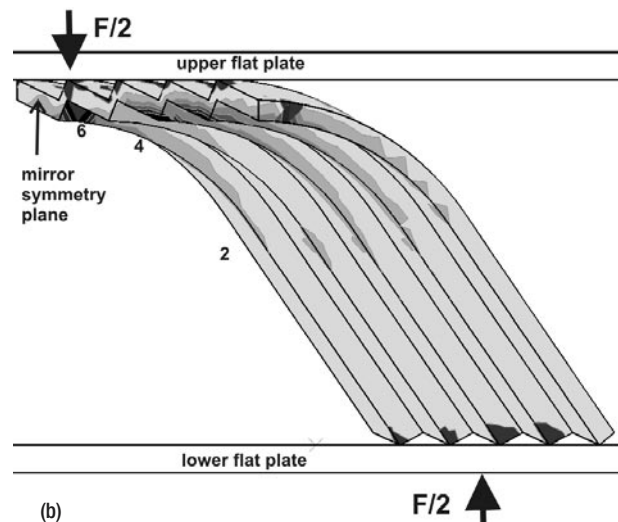
Soft tissue was modelled as a nearly-incompressible, gel-like material, using the hyperelastic model with Ogden shear moduli $\mu_1 = \mu_2 = 200 \text{ kPa}$, exponents $\alpha_1 = 2$ and $\alpha_2 = -2$, and inverse bulk modulus $D = 1.0 \times 10^{-9} \text{ Pa}^{-1}$ (Verdejo & Mills, 2002). The tibia was an elastic material with Young's modulus 11.5 GPa and Poisson's ratio 0.3 . The shells were taken as elastic materials, with a Young's modulus of 3 GPa for glassy thermoplastics, and Poisson's ratio 0.4 .

Guard shell geometry

Figure 3 shows two types of shell geometry analysed that were sections of a thin-walled cylinder having either a smooth surface or a surface ridged in the transverse direction at 18 mm intervals. The bending stiffness was analysed for the loading geometry used to test the commercial guards (see later). Mirror symmetry was used at the midplanes to reduce the size of the problem. For longitudinal stiffness the shell was encastre at one end, to represent the clamps. The guard thickness was kept at 3 mm , and the outline shape was simplified. The angular width of the half-shell is 0 to θ degrees, and its internal surface radius of curvature is r . For some shells (Figure 3b) the vertical section is first swept through an angle θ , then extruded linearly through a distance referred to as 'linear extrusion at side' in Table 1.



(a)



(b)

Figure 3 Bending stiffness tests, showing principal tensile stress contours: (a) a smooth shell loaded in the transverse test, (b) a ridged shell loaded in the longitudinal test.

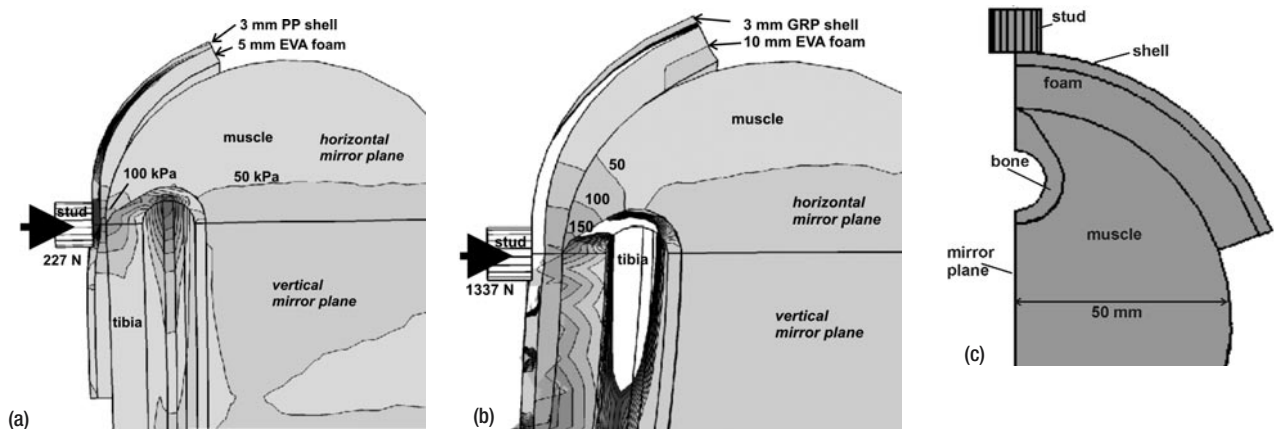
For the longitudinal stiffness, the shell length was 100 mm , and for the hoop stiffness its width was 100 mm . There were two layers of elements through the shell thickness.

Geometry of guard on lower leg

The tibia was modelled as a hollow cross-section tube, with the shape shown in Figure 4, of constant cross-section along its length. This differs from real tibia, which taper in section from end to centre. FEA of the tibia, loaded in three-point bending, showed that its

Table 1 FEA of shell bending stiffness (at 50 N total force).

Type	Shape	Shell inner radius mm	Half shell angular range θ degrees	Linear extrusion at side mm	Youngs modulus GPa	$[EI]_{\text{long}}$ Nm ²	$[EI]_{\text{trans}}$ Nm ²	$[EI]_{\text{trans}} / [EI]_{\text{long}}$
1	Part of cylinder	60	70	—	1.0	11.1	0.29	0.026
2	Part of cylinder	40	90	—	3.0	28.0	0.48	0.017
3	Umbro smooth	40	55	40	3.0	4.8	0.47	0.098
4	Umbro ridged	40	55	40	3.0	8.6	2.81	0.327

**Figure 4** FEA predictions of guard shape at maximum load, with contours of compressive stress kPa in the 2 direction: (a) 5 mm foam, shell modulus 1 GPa, (b) 10 mm foam, shell modulus 10 GPa. (c) shows the tibia cross-section shape.

bending stiffness in the anterior–posterior (A–P) direction was 180 Nm², identical to the Sawbones model. The tibia was placed symmetrically in the model; this made the FEA more stable, and the mirror plane symmetry cut the problem size. The muscle cover at the apex of the tibia was zero, and the external shape of the leg muscle was a cylinder of diameter 100 mm. The muscle was bonded to the tibia. The tibia is simply supported at both ends, to represent the free rotation of the ankle and knee joints.

The shell was assumed to have a smooth surface (Type 1 of Table 1) to simplify the FEA. Nevertheless, if the shell Young's modulus was 3 GPa, the 200 mm long shell has bending stiffness $[EI]_{\text{long}} = 33 \text{ Nm}^2$ and $[EI]_{\text{trans}} = 2 \text{ Nm}^2$, within a factor of two of the Umbro shell values. The guard foam, of thickness 5 or 10 mm, was bonded to the shell. A coefficient of friction between the foam and the muscle of 0.75 was used, to allow for sliding friction. To reduce the computation

time, two planes of mirror symmetry were used. The elements used were C3D3R (8-noded linear bricks with reduced integration) in ABAQUS 6.2 standard. The spacing of the FEA mesh was biased towards the initial impact point. Particular care was taken to see that the spacing of surface nodes was nearly continuous across material boundaries.

Results of FEA

Shell longitudinal bending stiffness

The effective longitudinal bending stiffness $[EI]_{\text{long}}$ of a cantilever beam of length L was calculated from the end deflection x mm, when an end load $F = 50 \text{ N}$ was applied using:

$$\frac{F}{x} = \frac{3EI}{L^3} \quad [7]$$

The value is effective, since the equation ignores the correction for the load being at a point, rather than spread uniformly across the end surface. It is a secant value; some response curves developed a negative curvature as the region near the load point curved over. For a shell with 40 mm internal radius and half-shell angular width $\theta = 90^\circ$, made from a glassy polymer with $E = 3$ GPa, $[EI]_{\text{long}} = 28 \text{ Nm}^2$ (Table 1). The predicted stiffness increases rapidly as θ increases. The difference between the smooth (4.8 Nm^2) and the ridged guard (8.6 Nm^2) is moderate, since the ridges are in the ‘wrong’ direction to optimize the bending stiffness.

Shell transverse bending stiffness

For a straight beam of width $w = 100$ mm, thickness $d = 3$ mm and Young’s modulus $E = 3$ GPa, $EI = Ewd^3/12 = 0.67 \text{ Nm}^2$. If curved beams are loaded in three-point bending, there are corrections to equation [7] for friction at the loading points, and for the different bending moment vs. position relationships. Nevertheless, the effective $[EI]_{\text{trans}}$ was estimated using the straight-beam equation [7], at a central force $2F = 50$ N (the loading span is $2L$). The transverse bending stiffness is proportional to the guard length, and most commercial products are longer (Table 2) than the 100 mm FEA model.

For the simulation in row 1 of Table 1, the low shell bending stiffness allows a significant shape change for a load of 50 N. For the other simulations, the maximum deflection is < 3 mm, and the force deflection relationship is nearly linear. For the ridged shell, the predicted $[EI]_{\text{trans}}$ would be $\approx 6 \text{ Nm}^2$ for a 200 mm long guard. The commercial guard, which tapers in width near the ankle, is slightly less stiff. The ridges in the Umbro shell provide much of the $[EI]_{\text{trans}}$, increasing the ratio of transverse to longitudinal bending stiffness.

Stud impact on a guarded leg

Runs were made for a range of shell Young’s modulus values (equivalent to varying the shell bending stiffness); the in-plane Young’s modulus of glass fibre reinforced thermosetting plastic (GRP) can easily reach 10 GPa, while a 1 GPa modulus is typical of semi-crystalline polypropylene (PP). In Figure 4a, for the low bending stiffness PP shell, the shell surface has *buckled* inwards due to the localised pressure from the stud. The initially convex shell is now locally concave near the stud. The foam compressive strain (and stress) is high near the stud, but low further away. Much of the sides of the shell have moved away from the muscle. The high bending stiffness GRP shell (Figure 4b) is sufficient to prevent buckling. There is a much greater area of contact between the foam and

Table 2 Shin guard component materials.

Shin guard	Mass g	Length mm	Foam			Shell		
			Polymer	Density kg m ⁻³	Thick mm	Material	Density kg m ⁻³	Thick mm
Adidas Basic	39	192	EVA	BL – 74	4.2	PP	908	1.80
Adidas Segmented	70	147	EVA	W – 97		PE	942	
Adidas Shelter	104	205	EVA	W – 95	3.0	PS	969	2.00
			PU	38	4.8			
			EVA@	W – 81	4.8			
Adidas Venom	93	220	EVA	B – 97	2.5	PP	874	2.50
			PU	38	4.9			
Grays Anatomical	114	310	EVA	71	10.5	Al	2700	1.50
Nike OSi	94	210	EVA	110	3.2	GRP	831	4.09
Umbro Armadillo	82	230	Confor	G – 93	4.0	PP	912	2
			VN	B – 73	5.0			

Foams: PU polyurethane, PP polypropylene, EVA ethylene vinyl acetate copolymer, VN vinyl nitrile rubber. @ a small tree-shaped piece directly under the shell. Polymers: PE polyethylene, GRP glass fibre reinforced plaster, PS polystyrene. Al(uminium). Masses with ankle protection removed, lengths of rigid part. Foam colours: G(reen), W(hite), B(lack), BL(ue)

the sides of the leg muscle than in Figure 4a, and the high strain area in the foam is much less localised. Hence more energy is absorbed before the pressure near the stud becomes excessive. When the shape of the interface between muscle and foam becomes unstable, the foam compressive stress is about 300 kPa, (but less for the last simulation in Table 3).

Table 3 FEA of guard (shell type 1) on a leg, loaded centrally by a stud.

Shell modulus E GPa	Foam thickness mm	Peak energy J	Peak force N	Peak stable deflection mm	Initial loading slope $N\ mm^{-1}$
1.0	5	0.57	227	5.0	44
2.4	5	2.04	492	7.8	72
5.0	5	4.27	828	9.7	84
3.0	10	11.47	1339	15.7	66
10.0	10	10.4	1596	15.9	81

The predicted force vs. deflection relationships (Figure 5) are nearly linear, and the slope increases as the shell stiffness increases. The force vs. deflection graphs were integrated to produce graphs of peak force vs. input energy (Figure 6), to allow easier comparison with experimental data for known energy impacts. The graphs have a negative curvature and are fairly close together. The peak energy in any simulation was 11 J, when the force was 1.4 kN – less than the force to fracture a tibia.

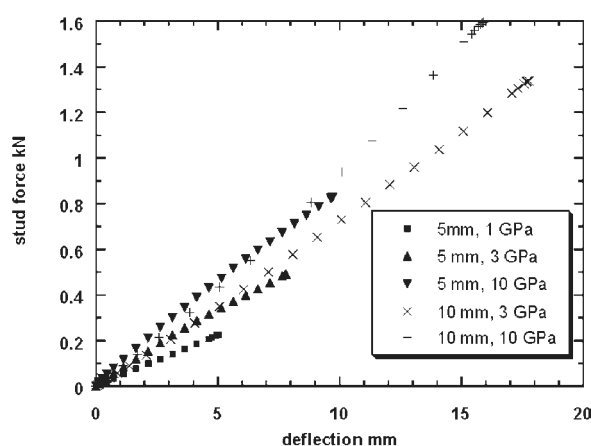


Figure 5 Predicted force vs. deflection relationship for single stud loading, for foam thickness and shell Young's modulus combinations.

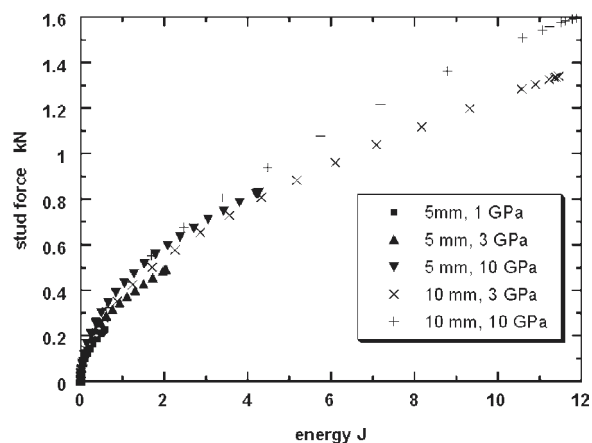


Figure 6 Peak force vs. input energy FEA, from an integral of Figure 4.

It was not possible to get stable FEA predictions for smooth or ridged shell with a gap between the foam and the front of the leg. There is instability in the sliding interaction between the foam and the muscle.

Experimental method

Shin guards tested

Figure 1 shows that most of the shin guards had a near-cylindrical shape; in (b) there are longitudinal ridges and slots to reduce the transverse bending stiffness and in (c) separate PE hollow tubes and spacers form a segmented structure. Table 2 details the guards tested – none were made to BSEN 13061. The only guard that contained special foam in front of the tibia was the Umbro guard, which had Confor slow-recovery foam in this area. The Nike OSi guard is moistened and moulded to the player's leg shape. The Gray hockey shin guard was examined to see the effect of an aluminium shell.

Shell bending stiffness

The shells were mounted as shown in Figure 3. For the longitudinal test, one end was clamped in a vice between suitably-shaped blocks of wood, while a point load of 50 N was applied to the centre of the other end. For the transverse stiffness, the shell was compressed between parallel flat plates in an Instron machine, with a load of 50 N applied.

Falling striker impact test

A single metal football stud was attached to a guided, vertically-falling plate and carriage of total mass 4.1 kg. Details of further tests with four studs are given by Ankrah (2002). The striker was fitted with a linear accelerometer, aligned vertically. Impact energies of < 5 J were used, to avoid damage to the tibia model. The deceleration data was converted to a 12-bit digital signal, sampled at 1 kHz. The striker force was calculated from the product of striker acceleration and mass, while numerical integration was used to calculate the deflection of the upper surface of the shin guard at the point of impact.

The artificial tibia used was a Sawbones Part No 3301. The soft tissue substitute, Senflex 435 foam, has similar indentation resistance as human soft tissue in the ankle area (Ankrah & Mills, 2003). The composite tibia, with its anterior crest exposed, is mounted in a slot in the 100 mm diameter foam cylinder. The tibia was supported horizontally at the distal and proximal end on shaped aluminium blocks, 230 mm apart (Figure 7a). The slight tension in the 2.0 mm thick SkinFx silicone rubber cosmetic skin (Endolite Chas A. Blatchford & Sons, Basingstoke, UK) held the components together during impact.

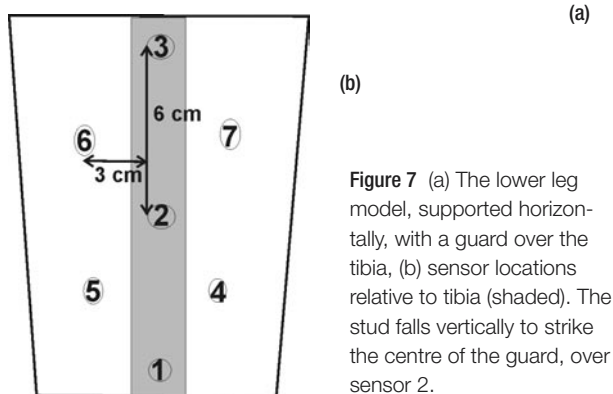


Figure 7 (a) The lower leg model, supported horizontally, with a guard over the tibia, (b) sensor locations relative to tibia (shaded). The stud falls vertically to strike the centre of the guard, over sensor 2.

High speed photography

A Kodak EM high-speed digital camera was used at 1000 frames per second for 4.2 seconds. To allow a clear view of the impact, the stud was placed on a 100 mm long cylindrical support. Shin guards were tested with an impact energy of 1.8 and 3.7 J.

Load distribution experiments

Tekscan Flexiforce sensors of load range 0 to 25 lb (pressure range 0 to 1.5 MPa) were mounted on the rubber skin, with three along the tibia and four on the 'soft tissue' (Figure 7b). The resistance of these 0.13 mm thick and 9.5 mm diameter sensors changes with the applied compressive force. Their calibration, when powered with a 5 V source and loaded on an Instron, was linear to within 5%. Their output was monitored using a PICO 11 bit analogue to digital converter. The stud was aligned with sensor 2.

Experimental results

Shell bending stiffness

The range of $[EI]_{\text{long}}$ from 5 to 25 Nm^2 for thermo-plastic shells (Table 4) is just below the FEA prediction of 28 Nm^2 for a shell with 40 mm internal radius and sweep angle $\theta = 90^\circ$, made from a glassy polymer with $E = 3$ GPa (Table 1). Hence the cylindrical shape provides the longitudinal bending stiffness. The $[EI]_{\text{trans}}$ of the Umbro guard, which tapers in width near the ankle, is slightly less stiff than the FEA prediction of ≈ 6 Nm^2 for a 200 mm long, ridged shell. The ridges in the Umbro shell provide much of the $[EI]_{\text{trans}}$, and increase the ratio of the transverse to longitudinal bending stiffness to about 0.15. This ratio

Table 4 Measured shin guard stiffness in transverse and longitudinal directions.

Shin guard	Bending Stiffness, EI (Nm^2)		
	Longitudinal	Transverse	$[EI]_{\text{trans}}/[EI]_{\text{long}}$
Adidas Basic	5.2	0.14	0.027
Adidas Segmented	4.0	0	0.0
Adidas Shelter	11.5	0.3	0.031
Adidas Venom	15.7	0.5	0.026
Nike OSi	10.9	0.6	0.055
Grays Anatomic	172.3	2.7	0.010
Umbro Armadillo	24.7	3.8	0.153

(Table 4) is much higher than the range 0.01 to 0.05 for all the smooth or nearly smooth shells.

Falling striker impact test

Figure 8 compares the stud force vs. deflection graph for a number of guards. For the Umbro guard, the force has a near plateau of 200 to 400 N. The maximum deflection is greater than for the other guards, due to the initial larger gap between the shell and the leg. For the other guards, the initial low slope is probably due to the compression of soft polyurethane foam. The greater slope later in the response is due to the shell buckling inward. At the maximum force of about 1 kN, the foam directly below the stud is about to bottom out (see the later section on pressure distribution). A comparison impact on the unprotected tibia was made with a polyurethane moulded blade, rather than a metal stud, to avoid damage. The force oscillations are due to the excitation of bending vibration modes in the tibia.

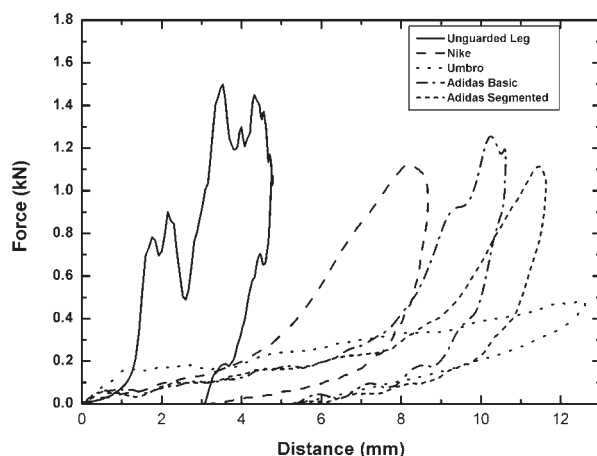


Figure 8 Striker force vs. shell deflection graphs for 5 J single stud impacts on various shin guards.

The predicted linear rise to a 200 N force at 5 mm deflection (Figure 5), for a shell modulus of 1 GPa and 5 mm of foam, is the same as the initial part of the experimental data (Figure 8) for other than the Umbro guard, validating the FEA.

High speed photography

The photographs showed that most shells buckled; for these shells there was little load spreading away from

the stud location. Figure 9 compares the Adidas Basic, which had buckled by a load of 696 N, with the Umbro Armadillo, which maintains its shape at a load of 583 N.

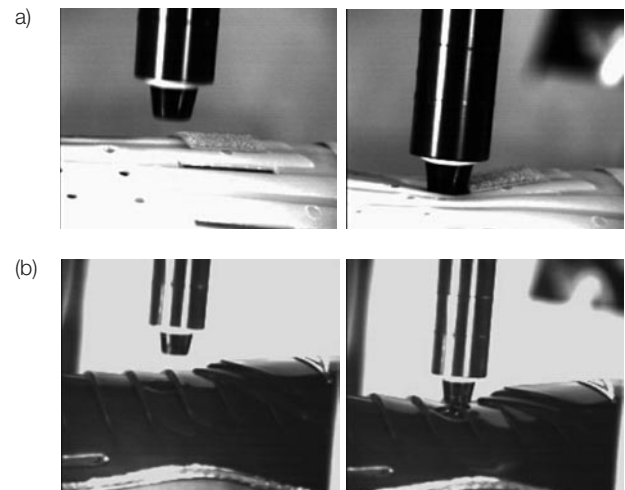


Figure 9 Frames from stud impacts before, and at peak deformation for a) Adidas Basic (b) Umbro Armadillo.

Load distribution experiments

The peak striker force (Table 5) was in the range 0.6 to 1.2 kN for the 3.7 J impacts. The peak local force of 86.7 N, on the tibia under the stud, occurred for two Adidas guards and the Nike guard. This corresponds with a peak pressure of 1.2 MPa. Measures of the load spreading away from the stud are:

Along the leg:

$$S_{\text{long}} = \frac{F_1 + F_3}{2F_2} \quad [8]$$

In the transverse direction:

$$S_{\text{trans}} = 0.75 \frac{F_4 + F_5 + F_6 + F_7}{F_1 + F_2 + F_3}$$

These measures are zero for no load spreading and unity for uniform pressure on the sensors. Figure 10 shows how the measures correlate with the shell bending stiffness, for the transverse and longitudinal directions. The correlation coefficients, for a linear relationship, are $r^2 = 0.63$ for the transverse direction (Figure 10a), and $r^2 = 0.84$ for the longitudinal direction (Figure 10b) if the Grays hockey guard with the

Table 5 Maximum forces for shin guards, impacted by a metal stud with 3.5 J energy.

Shin guard	Impact duration (ms)	Striker force (N)	Sensor force (N)						
			1	2	3	4	5	6	7
None (PU blade)	10	1231	1.9	80.9	0.4	0.1	0.3	0.1	0.1
Adidas Basic	15	1066	11.5	78.8	0.3	0.2	0.1	0.2	0.2
Adidas Segmented	15	867	11.2	86.7	1.3	0.3	0.3	0.1	0.2
Adidas Shelter	17	846	17.8	86.7	10.2	1.6	0.3	0.5	0.7
Adidas Venom	20	778	8.8	72.9	1.9	1.5	0.7	0.6	0.7
Grays	13	622	9.0	36.0	26.8	7.4	0.1	4.0	0.1
Nike	13	1096	6.6	86.7	1.0	0.4	0.1	0.2	0.2
Umbro	17	550	32.5	24.6	4.8	1.1	0.1	1.7	0.2

extremely high EI is ignored (0.49 if not). These correlation coefficients are reasonable given that the internal radius of the Umbro guard is smaller than the others, and the guard foams differ. The variation about the straight line fit appears to be random in Figure 10a, but the Umbro data point lies above the trend line in Figure

10b. The maximum values for load spreading are 0.8 for the longitudinal direction (Umbro) but only 0.12 for the transverse direction (Grays). These guards have the lowest peak forces on sensor 2 under the stud (Table 5).

The variation of the local forces with time (Figure 11) has a simple shape. It is likely that the total force

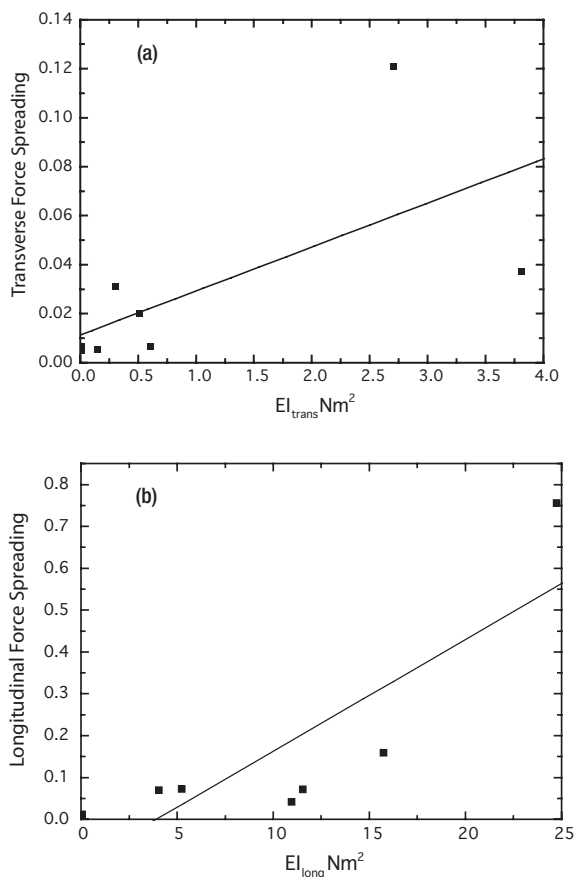


Figure 10 Experimental shell bending stiffness EI vs. the load spreading index in (a) transverse (b) longitudinal directions, with best-fit lines.

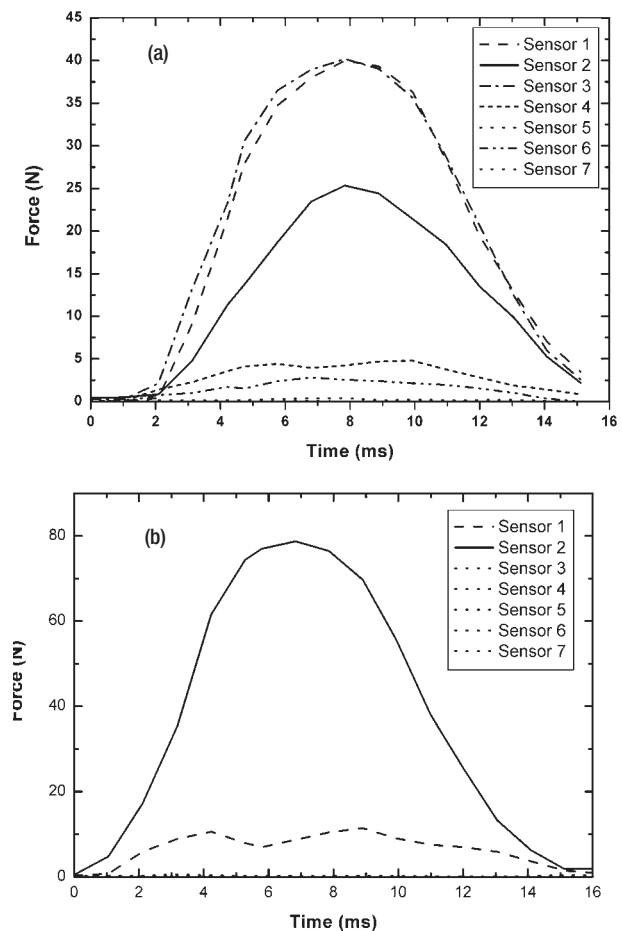


Figure 11 Variation of the local forces with time during impact on (a) Umbro, (b) Adidas basic guards.

can be modelled by an impact between two masses, and a contact stiffness, as in equation [1]. The nearly linear force vs. deflection response predicted by FEA (Figure 5) provides the value of the contact stiffness.

Discussion

The predicted forces (Figure 5) are within a factor of two of the experimental loading forces, at a given deflection, but greater than the experimental unloading forces. No attempt was made in the FEA to exactly match the complex shape and construction of many guards, for a more exact comparison. The predictions are for elastic materials that load and unload along the same path. The experimental hysteresis on unloading is due to viscoelasticity in the polymer shell, (which buckles then recovers) and in the foam (see Figure 2). The low guard mass, compared with the striker or leg, means that dynamic forces are insignificant; there are no force oscillations in the guard test traces (Figure 8). Hence there is no need to use explicit FEA to model such oscillations. Further FEA modelling of the leg muscle is needed to optimize the design of shin guards, and to consider other impact sites on the guard.

It is impractical for a shin guard to have a greater longitudinal bending stiffness than the tibia (180 Nm^2). However, it seems easier to spread load along the tibia than to its sides. The 4 Nm^2 transverse bending stiffness of the ridged Umbro shell is adequate to spread some load to the leg muscle. However, the shell inner radius of curvature was less than the leg radius, creating a gap between the shell and the anterior crest. More semi-rigid foam could be inserted into this gap, leaving a soft EVA foam layer in contact with the leg. Since oblique impacts have not been considered, it is not known if the ridged exterior risks excessive guard displacement in an oblique tackle.

The sides of the majority of guards lift from the leg muscle when they are impacted centrally with a stud. To avoid this, the shell transverse bending resistance must be increased considerably; one method is to use a high modulus (10 GPa), 3 mm thick, fibre-reinforced, composite shell. However, a thermoplastic shell with complex ridges might be lighter. The Umbro guard uses a thin layer of Confor 47 slow-recovery foam, rather than EVA foam. Davies & Mills (1999) showed

that this foam absorbs significant amounts of energy at impact rates, while conforming to the body shape when loaded slowly. However, it has very temperature-dependent properties, since its glass transition temperature is about 20°C .

Although the equivalent kinetic energy of a football kick was estimated at 10 J, test energies $> 5 \text{ J}$ were not used, for fear of damaging the test rig. This reflects on the modest protection levels afforded by current shin guards against stud impacts. In such impacts, there is a risk of muscle bruising at test energies much less than those needed to cause tibia fracture. The 2 J impact energy in the BSEN standard needs reconsideration; it is too low. At the same time, more research is needed into the effective impact energies from kicks; it might be possible to equip footballers with portable instrumentation to measure impact forces. It would also be useful to relate football players' contusion patterns to the type of shin guard worn.

It is recommended that test rigs simulate muscle, rather than use a wooden leg, to avoid false load transfer mechanisms. The local pressure measurements showed that many guards have a poor ability to distribute pressure from a stud in the transverse direction. Compared with previous research, which simulated leg to leg contact and protection against bone fracture, the impact energies that the guards could tolerate for stud impacts were lower. This shows how localised loading can readily cause bruising.

The materials design comments of Francisco *et al.* (2000) appear to be valid, so long as the foam used has a suitably high energy absorption. At present, materials selection is hindered by lack of knowledge of bruising criteria. If bruising occurs for pressures $> 1 \text{ MPa}$, some shin guards would allow bruising for a 4 J stud impact over the tibial crest. The shells have buckled and the foams bottomed out at this stage, so the pressure will rise rapidly for higher impact energies.

Conclusions

Shin guards on the market vary considerably in terms of the shell materials and shapes used, and shapes. FEA shows that transverse ridges can provide a high transverse bending stiffness for guard shells. FEA also shows that most shells will buckle under a direct stud

impact; the underlying foam can only absorb a significant energy if the shell resists buckling for impacts of kinetic energy of 10 J. High speed photography showed that most shells buckled under a stud impact. A test rig with a foam muscle simulant, which is a development of the rig of Francisco *et al.* (2000), is suitable for evaluating guards against stud impacts. Shin guards on the market vary considerably in their ability to distribute load, and none of them provide a high level of protection against stud impacts. A gap between the shell inner surface and the tibia is an effective method of increasing the protection of the tibia. Shells with this feature, and sufficient bending stiffness to avoid buckling under a central stud impact, such as in the Umbro guard, provided better protection than other guards.

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