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Design and manufacturing of shin pads with multi-material additive manufactured features for football players: A comparison with commercial shin pads

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Abstract

Shin pads are part of the mandatory equipment footballers must wear so as to prevent lesions. Most players wear commercially available shin pads made from a variety of common materials (polypropylene or polyethylene) and high-resistance materials (glass fibre, carbon fibre or Kevlar) using traditional manufacturing techniques. Additive manufacturing was used years ago to deliver customised rigid shin pads, but they did not offer any significant advantage in terms of materials or design compared to traditional shin pads. This project analyses a novel approach to the design and manufacture of shin pads for football players that combines existing digitisation tools, lattice structures and a multi-material additive manufacturing device. A total of 24 different additive manufacturing geometries were evaluated using a customised rig where a 1-kg impactor was released from several heights (100–400 mm). The impact acceleration, the transmitted force to the leg and penetration were calculated. Results were compared against two commercially available shin pads. Results show that two of the additive manufacturing specimens tested at the highest drop height had lower impact accelerations than commercial shin pads. They had an acceleration reduction between 42% and 68% with respect to the commercial shin pads. Regarding the penetration, the improvement achieved with additive manufacturing specimens ranged from 13% to 32%, while the attenuation and the contact times were similar.

Keywords

Shin pad, additive manufacturing, multi-material, lattice, impactor

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Introduction

Football is one of the most popular sports worldwide with more than 265 million male and female players.[1] Player injuries mostly occur in the lower extremities (87%), especially in the thigh, knee, ankle and hip.[2] Fractures represent 2%–11% of all football injuries and lower extremity fractures account for 30%–33% of all fractures, which occur while tackling (14.1%), being tackled (32.9%) or in a 50/50 tackle situation (50%).[3] In a study by Cattermole et al.,[3] 57% of tibia fractures were due to a three-point bending. However, within the literature it is not clear what type of impact is necessary to fracture a tibia, as both high-energy[4,5] and low-energy impacts[6] can be associated with this type of injury. There is also lack of unanimity regarding the peak force needed to fracture the tibia. Nyquist et al.[7] performed a dynamic bending test with cadaver tibias and concluded that a bending moment of 0.320 kNm was necessary to fracture a male tibia, while Kramer et al.[8] tested 209 deceased people and found that under

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the age of 60, no fractures occur, even with peak loads of 7 kN.

Shin pads have been evaluated in the literature through a variety of tests. Phillipens and Wismans[9] evaluated nine different shin pads and found that pads reduced the peak force by 28%–53%. Similarly, Bir et al.[10] used a pendulum impact apparatus and showed that peak impact forces were reduced between 40% and 77% when the pads were used. Lees and Cooper[11] obtained a reduction in peak impact force of between 40% and 60% and that the level of protection showed no correlation to the price of the pad. Francisco et al.[12] tested shin pads made of plastic, fibreglass and Kevlar by dropping an impactor from different heights. All the pads provided protection at all of the impactor's drop heights. Ankrah and Mills[13] carried out a falling striker impact test showing that shin pads on the market vary considerably in their ability to distribute load. Finally, Tatar et al.[14] evaluated three polypropylene and two carbon fibre shin pads under low (0.8 kN) and high (3 kN) severity impacts. Similar to other authors, they found that pads decreased the risk of serious injuries, but commercially available polypropylene-based shin pads did not provide sufficient protection against high impact forces. All these studies agree that shin pads are effective, but despite that fact that the incidence of football leg injuries decreased significantly since the introduction of the shin pad in 1990 (1996–2000: −20%; 2001–2005: −25%),[15] the effectiveness of shin pads against, for instance, tibia fracture is still under discussion. Shin pads are governed by the British Standard 13061:2009,[16] which subjects the shin pads to various tests. However, according to various authors, these tests are aimed at reducing the severity of laceration, contusion and skin puncture caused by impacts rather than preventing tibia fractures.[13,17]

The process of shin pads design should take into account parameters like manufacturing material and shape to produce a product that will prevent leg injuries. Most commercially available shin pads have a near-cylindrical shape, typically manufactured with a rigid outer cover and a soft inner shell.[13] For the outer cover, polypropylene or polyethylene is mainly used, although materials such as glass fibre, carbon fibre or Kevlar have also been introduced, especially for shin pads for professional football players. For the inner shell, the material is a low-density polymer with high shock absorption and biocompatible properties, like ethylene vinyl acetate (EVA) foam. In the literature, studies that evaluated the performance of commercial shin pads against impacts reported shin pads weights ranging from 37 to 216 g.[12–14]

Despite the high number of commercial shin pads available, both amateur and professional players demand customised shin pads. These shin pads feature high-resistance materials and the exact anthropometry of the footballer's legs is considered when creating them.

Creating these customised shin pads is a manual process. A replica of the leg is made from plaster of Paris, followed by the lay-up of composite material by using the replica as the master mould. Doctors are already applying new technologies when designing splints or protective devices for several body regions including the ankle–foot,[18–20] wrist[21,22] or face.[23] They involve the use of three-dimensional scanners to capture anatomical features, computer aided design (CAD) applications to model the device and additive manufacturing (AM) to build the designs from the three-dimensional (3D) data. Although the training and skill required to use the CAD modelling process can be time-consuming and cost prohibitive,[22] the new technological methodology allows a better fit of the protective device to the patient's body, since the design is based on accurate data from the 3D imaging. Moreover, the design process of the device can take advantage of the future AM process.

AM, also known as 3D printing, is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.[24] The layered nature of AM technologies offers design and manufacturing engineers a free-form fabrication method to build virtually any complex geometry. This allows them to create complex, light weight geometries in less time at lower cost than traditional manufacturing techniques. Other advantages of AM are the reduced material waste when manufacturing the part, reduction in the part counts and decreased iteration time when designing and testing a concept. As limitations, aside from the need for CAD modelling experience to design the virtual geometry, the resolution accuracy of the AM device and the minimisation of support geometries when printing are two aspects to consider.

Very few studies regarding 3D printed shin pads are found in the literature. Cazón-Martín et al.[25] developed some shin pads using the fused deposition modelling (FDM) technology and the material ULTEM 9085 from Stratasys (Stratasys Ltd, Minneapolis, MN, USA). The FDM pads did not represent any significant advantage in terms of materials or design with respect to traditional shin pads. A second design was the Zweinkampf shin guard.[26] The guard weighs 75 g and consists of three layers, approximately 7-mm thick in total, but only the external shell with a characteristic honeycomb structure was 3D printed by using the selective laser sintering (SLS) technology.

This work defines a novel methodology to design and manufacture shin pads for football players that combines existing digitisation tools to capture football player's legs and a multi-material AM device to print the pads. The specific goal is to explore if AM, as well as an appropriate design approach with lattice structures, can deliver customised shin pads that have better performance than commercially available shin pads with respect to the risk of tibia fractures. This performance is evaluated through impact studies with a customised test rig.

Materials and methods

The entire methodology was divided into six phases; each one involved several steps. The process started with the modelling of several cylindrical specimens that feature a lattice structure for shock absorption. These specimens were modelled considering the advantages and limitations of the later AM process. Then, specimens were printed using a multi-material AM printer to print the lattice structure in a shock-absorbing rubber-like material. Next, specimens were evaluated using a stud impact test and their performance was compared against two commercial shin pads. Later, the digitisation of the patient's legs was performed in order to obtain the virtual mesh of the leg. Next, a CAD model of the basic shape of the shin pad based on the virtual leg was created. Finally, the design incorporating the best lattice structure from the stud test was 3D printed.

Modelling specimens

A total of 24 specimens were modelled, manufactured and tested in order to analyse and determine an appropriate lattice structure that maintains a reasonable level of performance with respect to commercial shin pads. Since most shin pads have a near-cylindrical shape,[13] several cylindrical specimens were modelled in CREO 3.0 (PTC Corporate Headquarters, Needham, Massachusetts, USA). The inner diameter of each specimen was set to 110 mm after inspecting the geometry of commercial shin pads used as reference in this project for comparison purposes. Their length and width were set to 50 mm. Each specimen had three parts: an inner, a middle and an outer shell (Figure 1). The inner and outer shells are supposed to be rigid, while the middle shell is supposed to work as the shock-absorbing geometry. This last geometry was modelled with a lattice structure of cylindrical bars. The thickness of the inner (e3) and the lattice (e2) was fixed to 1 and 5 mm, respectively, while the outer shell thickness (e1), diameter of the cylindrical columns (vd), spacing between two adjacent columns (hs) and presence or absence of horizontal connections among columns (hd) were the variable parameters (Table 1). Several holes were created in the inner shell, not only to facilitate the removal

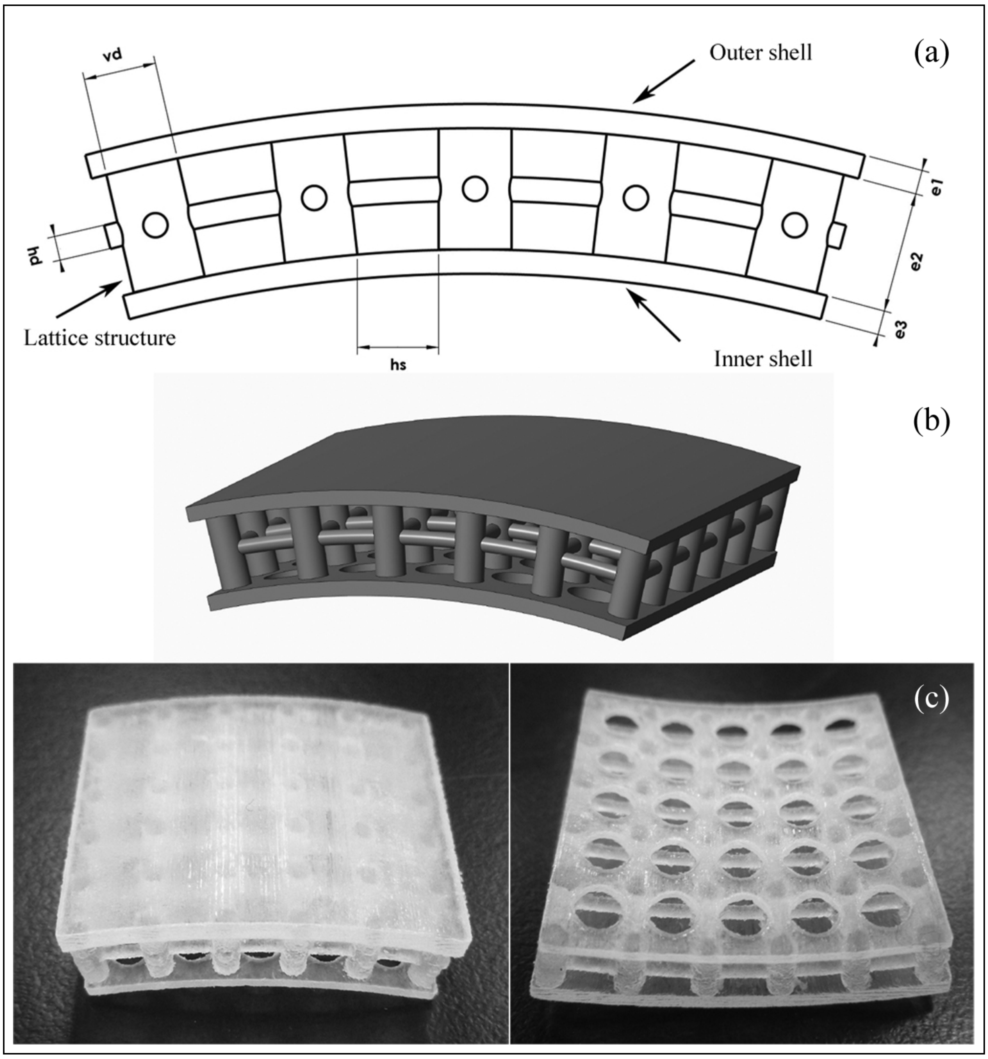

Figure 1. Cylindrical specimen: (a) schematics, (b) 3D model and (c) once printed. Lattice structure and holes for perspiration are clearly visible.

Table 1. The 24 printed specimens.

Specimen	e1 (mm)	vd (mm)	hs (mm)	hd (mm)	Weight (g)
1	1	2	2.5	1	3.1
2	1	2	2.5	–	2.8
3	1	2	3.5	1	2.8
4	1	2	3.5	–	2.5
5	1	3	2.5	1	3.4
6	1	3	2.5	–	3.3
7	1	3	3.5	1	3.0
8	1	3	3.5	–	2.9
9	2	2	2.5	1	4.2
10	2	2	2.5	–	4
11	2	2	3.5	1	3.9
12	2	2	3.5	–	3.7
13	2	3	2.5	1	4.7
14	2	3	2.5	–	4.6
15	2	3	3.5	1	4.3
16	2	3	3.5	–	4.0
17	3	2	2.5	1	5.4
18	3	2	2.5	–	5.2
19	3	2	3.5	1	5.1
20	3	2	3.5	–	4.9
21	3	3	2.5	1	5.9
22	3	3	2.5	–	5.7
23	3	3	3.5	1	5.5
24	3	3	3.5	–	5.3

e1: outer shell thickness; vd: diameter of the cylindrical columns; hs: spacing between two adjacent columns; hd: diameter of the horizontal connections (if present).

of the support material from the AM process but also to reduce the weight and increase perspiration of the future shin pad. This step ended with all the specimens exported to STL files for the printing process.

Additive manufacturing of specimens

The 24 specimens were printed to evaluate the suitability of these structures against impacts. The manufacturing process of the specimens was performed using the multiple material capabilities of an Objet Connex 3 260 printer (Stratasys Ltd., Minneapolis, MN, USA). The Connex printer uses three different photopolymer materials for printing: two are called ‘model material’ and the third is known as the ‘support material’. The two model materials used were the general purpose Fullcure 720 for the rigid parts and Fullcure 930 (called TangoPlus) for the lattice structure, while the support material was Fullcure 705. These materials were selected because they are the most common and cheapest materials to obtain rigid and soft parts. According to Stratasys, Fullcure 720 features an elastic modulus between 2000 and 3000 MPa with a tensile strength of 50–65 MPa. TangoPlus has a shore hardness (A) of 26–28. All specimens were printed with the same orientation. One of the printed specimens is shown in Figure 1. The weight of each individual specimen, after removing the support material, is shown in Table 1.

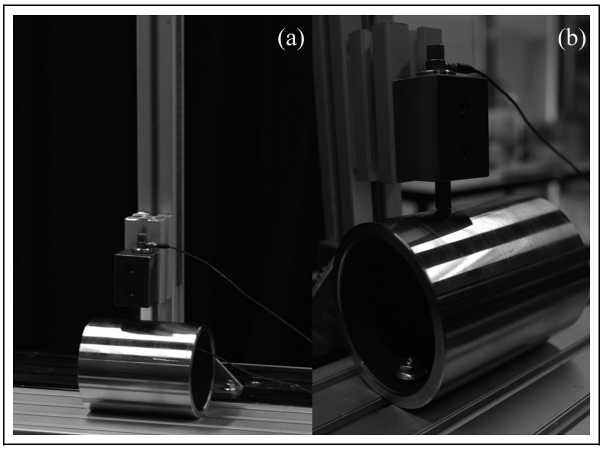

Figure 2. Overview of the test rig: (a) a detailed view of the impactor and the stud and (b) digitising.

Testing specimens

To compare the performance of the manufactured lattice structures, several impact tests were performed using a customised test rig. The test rig consists of two different parts (Figure 2). One was a steel tube of 110 mm diameter, rigidly attached to an aluminium plate placed on the ground. The other was an impactor or falling block with a mass of 1 kg placed in a vertical guidance system. The block had a cylindrical steel stud, mimicking a football cleat, which was 10 mm in diameter and projected 19 mm from the surface. This test rig was selected because it has been commonly used by other researchers to test shin pads by means of a falling impactor. The test rig was very similar to the one used by Francisco et al.[12] and Ankrah and Mills[13] with the exception of the steel tube that mimicked the tibia, as opposed to a rubber-covered foam leg and composite tibia, respectively, used by other authors. In this study, the 24 printed specimens were tested along with two commercially available shin pads. Each time, AM specimens were placed face up and affixed to the tube with tape, while the striker was positioned at a height just prior to releasing it. The impactor drop heights were 100, 200, 300 and 400 mm, which corresponded with expected impact velocities of 1.4, 2.0, 2.4 and 2.8 m/s, respectively, when all potential energy transferred to kinetic energy. Experiments began with the lowest height (100 mm). After completing tests at the 100 mm height, the specimens that did not break were printed again and tested at the next height (200 mm). Surviving specimens from the height of 200 mm were printed again and tested at 300 mm. Finally, the specimens that did not fracture during the 300-mm height test were manufactured again and tested at 400 mm. The two commercially available shin pads tested were the AdidasTM Predator Lite and AdidasTM Ghost Guard. Each one has a hard outer shell made of plastic and an inner layer of soft foam. The Predator Lite model features an external rigid shell made of 2.5 mm of polypropylene and a 5-mm internal foam structure made of

Table 2. Acceleration (m/s^2) of the impactor depending on the drop height.

Specimen	Drop height (mm)			
	100	200	300	400
1	465	948(F)	–	–
2	524 (F)	–	–	–
3	448	901 (F)	–	–
4	459 (F)	–	–	–
5	489 (F)	–	–	–
6	390 (F)	–	–	–
7	436 (F)	–	–	–
8	392 (F)	–	–	–
9	504	827	906 (F)	–
10	472	524 (F)	–	–
11	445	804	927 (F)	–
12	432	692 (F)	–	–
13	510	879	692 (F)	–
14	511	659 (F)	–	–
15	566	672 (F)	–	–
16	484	843	862 (F)	–
17	454	888	742 (F)	–
18	500	868 (F)	–	–
19	437	1210	967	1357
20	394	706	1251	1137
21	760	665 (F)	–	–
22	759	1211	797 (F)	–
23	676	1153	1411	1233(F)
24	642	970 (F)	–	–
Predator Lite	498	1808	2880	3623
Ghost Guard	353	621	1213	2376

F denotes a specimen that fractured while testing.

Table 3. Shock-absorbing ratio (%) between impact and transmitted force depending on the drop height.

Specimen	Drop height (mm)			
	100	200	300	400
1	85.1	83.3 (F)	–	–
2	78.9 (F)	–	–	–
3	85.9	88.2 (F)	–	–
4	86.7 (F)	–	–	–
5	81.7 (F)	–	–	–
6	84.0 (F)	–	–	–
7	82.5 (F)	–	–	–
8	81.5 (F)	–	–	–
9	83.1	83.1	80.0 (F)	–
10	83.8	79.1 (F)	–	–
11	82.7	83.8	88.5 (F)	–
12	82.3	85.7 (F)	–	–
13	80.6	80.1	78.3 (F)	–
14	80.6	78.9 (F)	–	–
15	78.6	85.2 (F)	–	–
16	82.3	79.4	85.5 (F)	–
17	77.7	80.3	82.2 (F)	–
18	79.3	79.9 (F)	–	–
19	81.4	80.5	76.4	81
20	75.1	80.8	82.1	77.9
21	75.3	76.7 (F)	–	–
22	74.7	88.4	75.1 (F)	–
23	75.1	74.9	71.7	77.6 (F)
24	75.6	77.8 (F)	–	–
Predator Lite	89.2	81.9	78.6	78.9
Ghost Guard	80.4	86.9	85	79.4

F denotes a specimen that fractured while testing.

85% EVA and 15% polyethylene. The external shell of the Ghost Guard model was made of 3 mm of polypropylene, while the 6.5-mm inner layer was made of 30% EVA and 70% polyethylene. The commercial shin pads were cut with a saw to obtain specimens with lengths and widths similar to those of the 24 AM specimens. The weight of the Predator Lite specimen was 3.4 g, while the specimen of the Ghost Guard model weighed 3.5 g. The testing procedure for these two specimens was as follows. Experiments began with the lowest height (100 mm). After completing the test at 100 mm, each specimen was visually inspected to verify the lack of cracks or damage to the external shell and inner foam. If the specimen passed the visual inspection, tests were run at 200 mm and the specimens were later inspected. The same procedure was applied for the heights of 300 and 400 mm.

The impactor acceleration was measured by a 500*g* accelerometer model 352C03 (PCB Piezotronics, Depew, New York, USA), while the attenuated acceleration in the tube was recorded with a second accelerometer of the same model, both aligned in the dropping direction. The sampling rate was 10 kHz. The penetration of the stud at the point of impact was obtained by a double integration of the acceleration signal. A MotionXtra HG-LE high-speed digital camera (IDT Redlake, Hitchin, UK) recorded the impacts at 2000 frames per second. The penetration values obtained via acceleration were validated against the images of the high-speed camera.

Digitising

The process of digitising the patient's legs was performed with the Sense 3D scanner from 3D Systems (Rock Hill, South Carolina, USA). For the scanning process, the football player had to stand for 10 s, while a technician moved the scanner to capture both legs. The resulting geometry was defined by 178,394 triangles in STL format. The average length for the edges of all triangles was 2.4 mm.

Modelling and additive manufacturing of shin pads

The shin pads were designed according to player's preferences using the Rhinoceros 5.0 CAD application and taking as reference the scanned legs. The shin pads incorporated the most appropriate lattice structure obtained from the test phase.

Results

Results from testing phase are shown in Tables 2–5. Figure 3 shows the images from the high-speed camera for the two best AM designs. Pads with a thicker outer

Table 4. Penetration (mm) depending on the drop height.

Specimen	Drop height (mm)			
	100	200	300	400
1	3.6	5.3 (F)	–	–
2	2.9 (F)	–	–	–
3	4.2	5.5 (F)	–	–
4	4.0 (F)	–	–	–
5	3.2 (F)	–	–	–
6	3.5 (F)	–	–	–
7	3.8 (F)	–	–	–
8	3.8 (F)	–	–	–
9	3.1	4	5.6 (F)	–
10	3.3	5.8 (F)	–	–
11	3.3	4.5	6.6 (F)	–
12	3.3	5.5 (F)	–	–
13	2.9	3.5	5.5 (F)	–
14	2.8	4.2 (F)	–	–
15	2.4	4.3 (F)	–	–
16	3.5	3.5	5.4 (F)	–
17	3	3.5	6.4 (F)	–
18	1.9	4.2 (F)	–	–
19	3.2	3.6	4.2	4.8
20	2.2	4.5	4.8	5
21	1.8	3.8 (F)	–	–
22	1.9	2.4	5.1 (F)	–
23	2	2.5	3	5.1 (F)
24	2.2	3.8 (F)	–	–
Predator Lite	4.4	5.1	5.3	5.8
Ghost Guard	3.8	5.5	6.7	7.1

F denotes a specimen that fractured while testing.

Table 5. Contact time (ms) depending on the drop height.

Specimen	Drop height (mm)			
	100	200	300	400
1	9.5	9.1 (F)	–	–
2	9.8 (F)	–	–	–
3	9.3	9.5 (F)	–	–
4	10 (F)	–	–	–
5	9.9 (F)	–	–	–
6	9.2 (F)	–	–	–
7	9.8 (F)	–	–	–
8	9.8 (F)	–	–	–
9	9.5	8.7	9.2 (F)	–
10	8.3	10.5 (F)	–	–
11	7.2	9.3	9.8 (F)	–
12	8.2	9.9 (F)	–	–
13	6.8	7.8	9.3 (F)	–
14	6.2	9.3 (F)	–	–
15	6.6	8.9 (F)	–	–
16	7	7.5	9.9 (F)	–
17	9.5	7.7	10.2 (F)	–
18	7.5	9.9 (F)	–	–
19	6.4	9.4	8.8	8.8
20	8.6	7.3	9.4	9.3
21	4.3	9.9 (F)	–	–
22	4.1	4.3	8.9 (F)	–
23	4.4	4.4	3.3	9.4 (F)
24	4.7	8.1 (F)	–	–
Predator Lite	10.8	8.2	8.5	8.6
Ghost Guard	9.9	9.8	9.3	9.3

F denotes a specimen that fractured while testing.

shell were characterised by supporting higher impacts without fracturing, independent of the lattice structure used. Only two lattice designs (#19 and #20) were capable of passing the most adverse scenario. Both designs have a total thickness of 9 mm, a value similar to the commercial pads. For the lattice, AM specimen #19 has vertical columns of 2 mm in diameter and horizontal connections for the columns, while specimen #20 features vertical columns of 2 mm and no horizontal connections. Considering Table 2, which shows the acceleration of the impactor at a given drop height, the acceleration values for specimens #19 and #20 were lower than the values for the two commercial shin pads. In addition, the shock-absorbing percentages (Table 3) of the two AM specimens were 81% and 77.9%, as compared to the two commercial specimens which were 78.9% and 79.4%. The results indicate that the force transmitted from the impact to the player's leg is lower for the two AM specimens than the commercial specimens. In addition, the penetration values of the AM specimens shown in Table 4 indicate that the penetration is also lower relative to the commercial shin pads. Finally, the contact times were found to be similar among the two AM and two commercial specimens (8.6–9.3 ms).

Figure 4 shows the impact force relative to penetration. The response of the commercial shin pads clearly differs from the AM specimens. The commercial shin pads show an initial low slope due to the soft foam that allows great deformation, but little stopping capacity. Beyond a certain point, the foam starts stiffening very rapidly and with the help of the shell buckling, the slope increases. The AM specimens show a more constant slope from the beginning of the impact: specimen #19, which has the horizontal links, presents on average a stiffer slope than specimen #20, which does not have the horizontal links.

Of the two best designs, the lattice of specimen #19 was selected for the design process. The shin pad, modelled in Rhinoceros following the player's design guides, is shown in Figure 5 with a length of 170 mm and a width of 110 mm. Printing this shin pad took 6.25 h, 234 g of Fullcure 720, 32 g of TangoPlus and 442 g of support material. The support material was removed using water pressure and hand tools. The AM shin pad had a final weight of 100 g and is shown in Figure 5.

Discussion

This article describes a new approach for the design and manufacture of shin pads for football players that takes advantage of the current multi-material capabilities of AM technologies. However, several points of this work deserve discussion.

Regarding the design itself, specifically the selected lattice structure, authors selected a simple geometry to

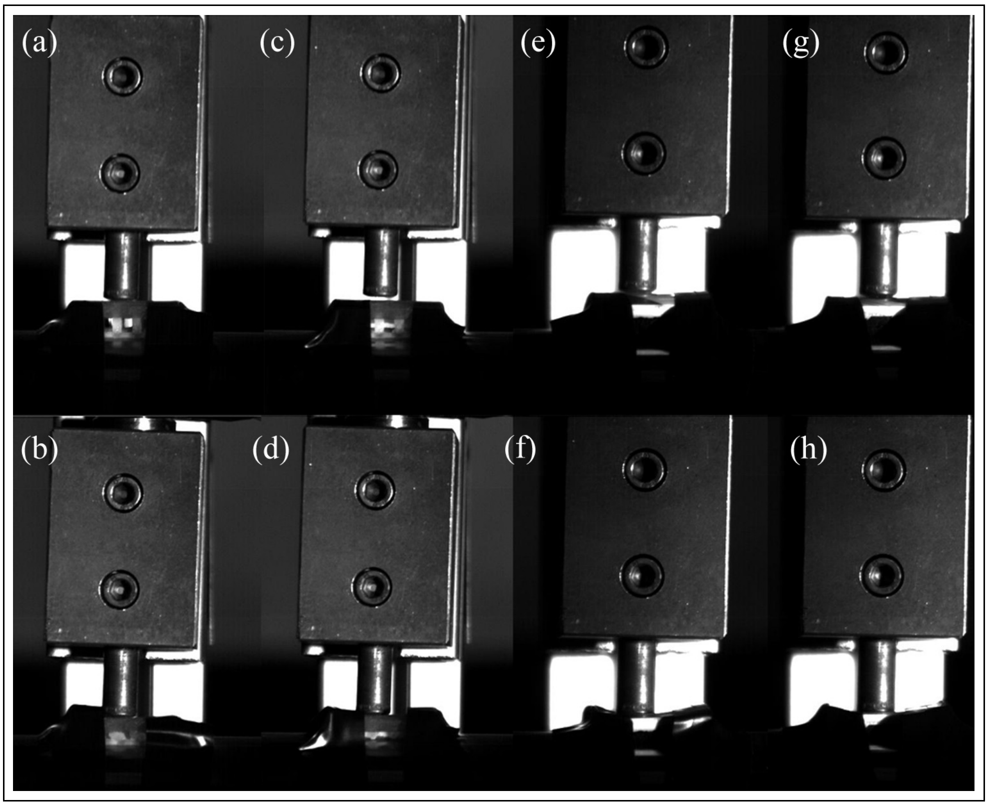

Figure 3. High-speed camera images showing the stud before and at peak deformation for 4 J (40 cm) experiment: Specimens #19 (a and b) and #20 (c and d), Adidas Ghost Guard (e and f) and Adidas Predator Lite (g and h).

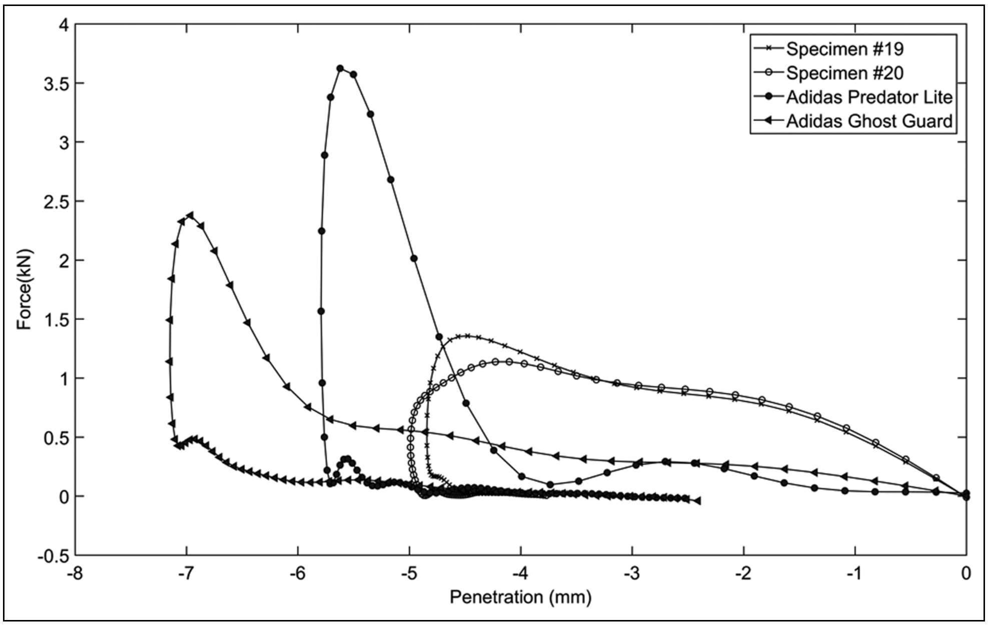

Figure 4. Impact force versus penetration for 4 J (40 cm) single stud impacts for specimens #19 and #20 and for the two commercial specimens.

verify that this novel approach was viable. As a first approach, this simple geometry was an attempt to mimic a collection of springs parallel to the impact direction and whose stiffness was based on the diameter of the cylindrical columns. The design of the lattice structure also considered the limitations of the subsequent manufacturing process, in particular, the removal of the support material by water jet. This manufacturing limitation led to the design of thick geometries greater than 2 mm (vd) that could not be damaged or

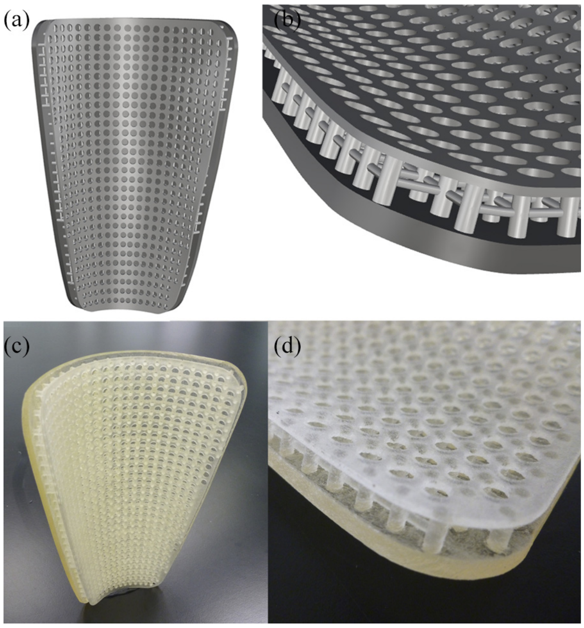

Figure 5. Final 3D model of the shin pad in Rhinoceros (a and b) and additive manufactured shin pad (c and d).

separated from the outer and inner shells due to the water jet. In addition, the final design incorporated enough spacing between the outer and inner shell (e2) and among the columns (hs) with some holes in the inner shell to help with the removal of the support material. The dimensions when designing all the specimens were selected according to the experience of the research team with the capabilities of the Connex printer and the final compromise between weight and protection that the shin pads should offer to the player. The authors did not have a software application for easy design of complicated lattice geometries and verification of the best design to withstand the impact.

Moreover, if a simultaneous multi-material printer is not available (i.e. the shin pad has to be printed fully rigid) another AM technology, such as SLS, could be selected in order to remove the support material more easily. In this case, several strategies could be adopted so as to create rigid lattice cell type structures with high impact absorption properties.[27] The use of the finite element method could help to compare different designs before printing them.

Regarding manufacturing, the authors set the printing parameters, such as material, printing orientation and resolution, so they were not part of the degrees of freedom. Nevertheless, this should be further investigated since some of them could be key parameters. For instance, the authors found that when the specimen failed during testing, the fracture always occurred in the outer shell. According to other authors,[12,14] the performance of a shin pad is related to both the thickness of the outer shell and the material it was made of, meaning that a thinner but stronger outer shell is equal to a thicker but less rigid material. A compromise between weight and protection should be considered in order to improve the player's comfort. In this study, selecting a stronger printing material and/or changing the printing orientation to consider the implicit anisotropies resulting from the AM methods could improve the presented prototype. In addition, ageing could have direct consequences in the variation of the mechanical properties because of the player's actual use of the shin pad and the shin pad's exposure to extreme temperature and wet and/or humid conditions. Therefore, the long-term properties of the materials need to be investigated to ascertain adequate service life.

Regarding test conditions, shin pads currently available in the market ensure proper protection by means of physical tests under the British Standard BS 13061. However, as some authors have mentioned, the impact tests are not demanding, and their impact energies are not justified in any way.[28] In one test, a stud of diameter 10 mm in diameter, attached to a 1 kg mass, makes an almost-tangential (10°) impact at $5.4\,m\,s^{-1}$ when falling from 1500 mm (15 J). The pads 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 and radius of corner 2 mm) with 2 J of kinetic energy, the peak force allowed is 2 kN. Ankrah and Mills[13] did some calculations considering the elements involved in gameplay and concluded that the equivalent kinetic energy of 10 J is representative of a football kick during gameplay. Some authors changed the regulation settings and test rig when evaluating shin pads in order to create 'worse' testing conditions.

Lees and Cooper[11] measured shin pad performance under 20 J impact by using a 5-kg mass dropped from 400 mm on pads mounted on a wooden leg. Ankrah and Mills[13] used a 4.1-kg impactor to obtain impact energies of 3.5 J on shin pads mounted on artificial tibias with similar resistance to human soft tissue. Francisco et al.[12] evaluated the effectiveness of a number of shin guards with a 4.2-kg impactor falling from heights of up to 500 mm, that is, a 20-J impact. The shin pads were tested on a leg model composed of a rubber-covered foam leg surrounding the synthetic bone. Phillipens and Wismans[9] used a spring-loaded guided impactor of 6.8 kg that hits the shin pad at 1.25 m/s (5.3 J). The shin pad was attached to a rigid wooden cylinder 100 mm in diameter. Bir et al.[10] tested 11 pads using a swinging pendulum that hit the shin pad mounted on the tibia region of a 5th percentile Hybrid III female dummy. In this study, the authors tried to follow this 'worsening' approach by choosing a lower energy impact (4 J), but with boundary conditions that were more severe. On one hand, the severity of the impact was worse when using a steel cylindrical base instead of a realistic deformable tibia. This meant lower deformation of the base and, as a consequence, higher acceleration and impact force. On the other hand, the current authors were testing a portion of the shin pad, instead of the full shin pad, as other authors had. This meant that only that portion of the shin pad absorbed the impact energy, instead of the entire shin pad. These testing conditions allowed the authors to quantitatively compare the AM designs against the commercial pads under a scenario more demanding than the one proposed by the regulation. However, using only a portion of the shin pad must also be considered as a limitation when comparing this study to others in the literature that tested the entire shin pad.

In addition, only two mass produced shin pads were used for comparison purposes. Although other models with stronger materials for the outer shell, such as fibreglass or Kevlar, could have been studied and compared against the AM specimens, the results would have been similar according to Francisco et al.[12] results. In their study, they did not find significant differences in the maximum impact force or contact time among several commercial shin pads made of common thermoplastic, Kevlar and glass fibre. However, Tatar et al.[14] found a correlation in the impact force for three polypropylene and two custom-made carbon fibre shin pads. More research and a comparison with carbon fibre shin pads are needed.

Analysing the results of the experiments, specimens #19 and #20 presented the best behaviour based on a combination of factors. First of all, they had a thicker external shell that reduced the risk of cracks due to the impact. However, more thickness did not necessarily mean better performance since the remaining six specimens that also featured a 3-mm thickness for the external shell failed. Second, the geometry of the lattice structure, and in particular the spacing among the cells, was another important aspect. Specimens #19 and #20 with high hs and the low vd feature the weakest lattice structure: the penetration values were higher meaning that the impactor decelerated slower without getting the external shell to critical levels. On the contrary, other specimens with high vd and low hs were more rigid and the resulting deceleration of the impactor higher. This higher deceleration led to permanent damage of the external shell.

The cost of a single shin pad following this novel approach was approximately €100 (USD116). This cost, which assumes only the cost of the 3D printing materials, is very expensive relative to the cost of a pair of commercial shin pads, which can cost from €5 (USD6) to €50 (USD60) and is geared towards mass production. However, the cost of AM shin pad is not so expensive when compared to customised shin pads. The football player who took part in this study noted that he usually wears a pair of customised shin pads made of carbon fibre that cost €600 (USD697). Comparing this cost to the AM shin pad cost, the AM approach can be very competitive.

Conclusion

This study has documented that, from a technical point of view, the multi-material AM approach for manufacturing shin pads is feasible, justifying further research and development. The authors have proposed a new design for shin pads consisting of a sandwich structure: two rigid layers (outer and inner) and a middle layer that has a lattice structure that works as a shock-absorbing geometry. To compare the performance of the different lattice structures, several impact tests were performed using a customised test rig. The AM designs were dynamically tested along with two commercially available shin pads by using an impactor of 1 kg that was dropped from heights of 100, 200, 300 and 400 mm. The results show that two of the AM specimens had acceleration reductions between 42% and 68% with respect to the commercial shin pads, while the penetration was reduced 13%–32%. The attenuation and the contact times were similar. The best lattice structure was used to design a real scale shin pad in Rhinoceros that was later physically prototyped with the help of a multi-material AM printer. These results reaffirm the possibilities explored by other researchers and help to dispel the major concern of players and team medical doctors: AM technologies are a real solution for football personal protection equipment designs because they are able to withstand severe impacts that are representative of a kicking foot, thus minimising the risk of tibia fractures.

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