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SynTissue® as a surrogate material for the human scalp

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ABSTRACT

Synthetic skin produced by SynDaver®, currently used primarily in medical testing and training applications, may be suitable as a surrogate for human skin in forensic investigations. To determine how accurately the company's synthetic skin, SynTissue®, could mimic the mechanical properties of human skin, tests were conducted to measure its elastic modulus and resistance to laceration. Test results were compared to published data acquired from tensile tests conducted on human scalp and impacts with blunt objects on porcine heads. The stress vs strain relation for SynTissue® 8 N corresponded closely to that of the human scalp. Deformations similar to skin lacerations were observed when SynTissue® was subjected to blunt object impacts, at forces in the range of those reported for lacerations of cadaver and porcine heads. However, the published data are insufficient to unequivocally assess the suitability of SynTissue® for forensic investigations of lacerations. Moreover, there are features of the SynTissue® impact deformations that can provide useful information even if the laceration threshold turns out to be lower than that of human skin.

1. Introduction

Trauma to the head from impacts such as those sustained from a fall, being struck by a blunt object or by a projectile, involves deformation of the scalp or facial skin. Being able to test a material with similar mechanical properties to the skin covering the head can be useful in forensic investigations for establishing the mechanism of injury or the potential severity of a head injury. In particular, due to procurement and ethical issues, including cost, using human skin or animal surrogate skin is often not feasible or practical when a large number of tests are required to obtain the necessary data. Several previous studies have proposed different materials as surrogates for the human scalp. These include silicone [15] and polydimethylsiloxane [11], both of which have similar mechanical properties to human skin. A recently developed viscoelastic material, manufactured by SynDaver® (Tampa, FL), is being used to simulate the mechanical properties of human tissues in medical testing and training applications [10,13]. Sheets of the material, marketed as SynTissue® plates, are designed to replicate the mechanical properties of the skin, with selections for different force penetration characteristics. Plates of SynTissue® are available in various thicknesses, representing different penetration forces. The research question which we addressed was whether the SynTissue® could replicate specific mechanical properties of the human scalp. If so, it could represent a surrogate material suitable as a substitute for human skin in forensic testing of head injuries.

The mechanical properties which we tested were the elastic modulus and deformation produced by blunt force trauma. Several studies have been carried out to investigate the stress vs strain characteristics of the human scalp with tissue samples obtained during surgical procedures [6] or from cadavers [16,4,7] or by directly applying force to skin flaps during scalp reduction surgical procedures [5]. These studies found that the elastic modulus of the human scalp was in the range of 15 MPa to 38 MPa. Compared to scalp tensile properties, there is relatively little published quantitative research related to the impact force required to produce deformation such as laceration of the scalp using a blunt object. Furthermore, the occurrence of a laceration may depend on factors other than the impact force, such as the shape of the object and the thickness of the skin. Therefore, comparison with published values of impact force associated with scalp laceration were used only as benchmarks to determine whether laceration of SynTissue® occurred within a similar range of impact forces. Lee et al. [9] calculated the velocity of impact of a crash block dropped onto cadaver heads and calculated the impact force from the estimated work done to create the laceration of the scalp. Their estimate of the impact force was based on the assumption that stopping distance of the crash block was 3 cm. The stopping distance was not directly measured so their estimated impact force of 2145 N may not

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have been accurate. Sharkey et al. [14] used a similar method to calculate the average impact force of a hammer dropped onto a porcine head, although displacement was determined from acceleration measurements rather than estimates. They found lacerations at their lowest impact force of 4149 N, although lacerations were sometimes not found for higher forces, e.g. 7797 N, which produced skull fractures. Although scalp thickness and mechanical properties have been reported to be similar for porcine and human scalp, differences such as skin contour and methods used to estimate impact force may account for the differences. Whereas these values cannot provide a definitive laceration threshold for the human scalp, which may depend on factors in addition to impact force, they provides a ballpark range for comparison purposes. Thus, the above cited values for elastic modulus and minimum impact force for blunt trauma lacerations were used as references for judging the suitability of SynTissue® as a surrogate for the human scalp in forensic investigations.

2. Materials and methods

2.1. Elastic modulus protocol

SynTissue® 2 N (thickness 1.34 mm), 4 N (thickness 1.21 mm) and 8 N (thickness 1.16 mm) plates were tested to determine which best matched the elastic modulus of the human scalp. SynTissue® was

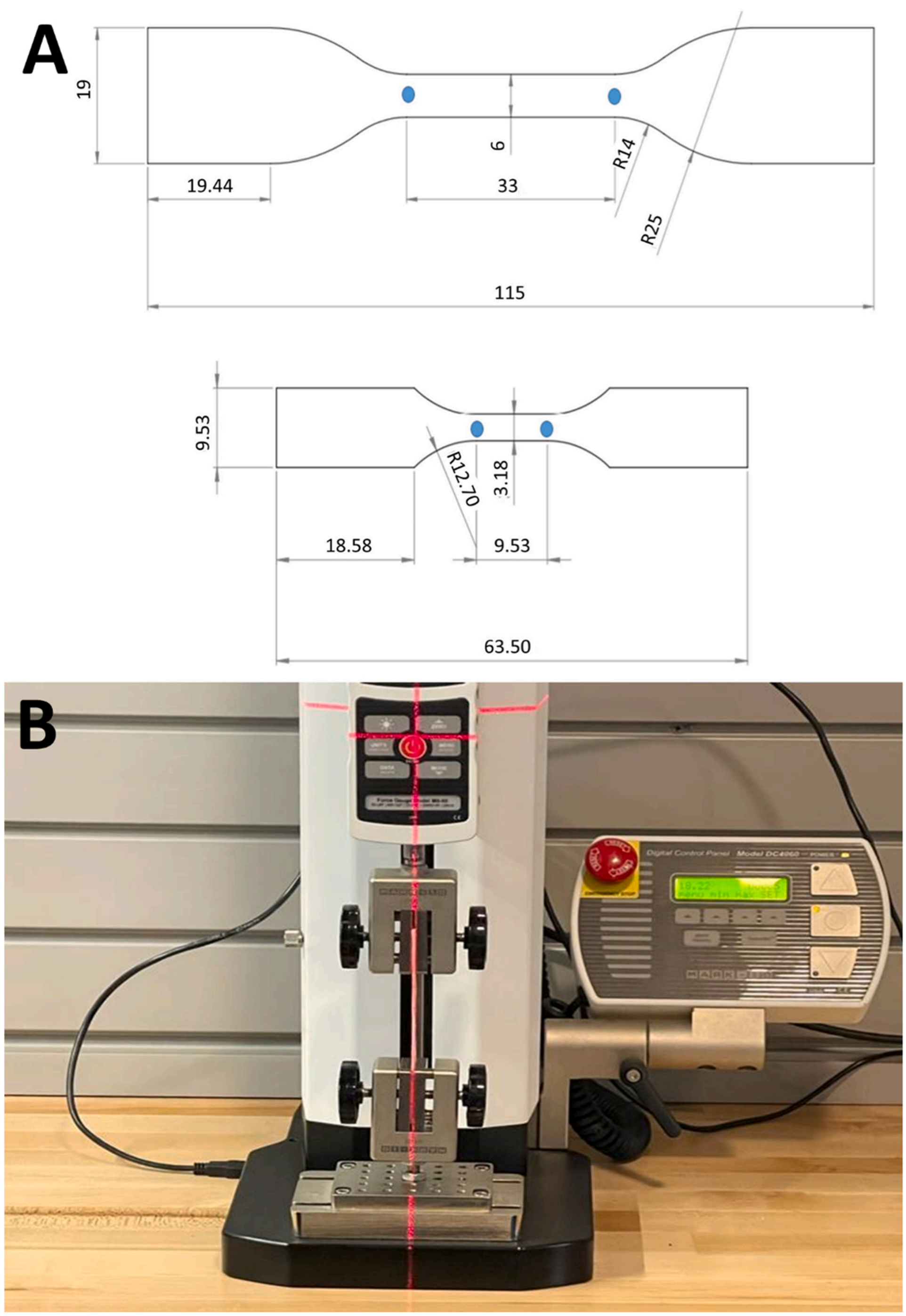

Fig. 1. A. Geometry of SynTissue® dog-bone samples used in testing. Templates were created using CAD software based on ASTM guidelines. B. Mark-10 Tensile Tester set up for testing of SynTissue® dog-bone samples.

prepared according to the manufacturer's instructions to ensure that its moisture content was retained during testing. Dog-bone samples were cut from each SynTissue® plate, based on the ASTM (American Society for Testing of Materials) guidelines, as illustrated in Fig. 1A. Both 3.18 mm and 6 mm dog-bone widths are specified in the ASTM guidelines so both were tested to determine whether they produced similar results. The dog-bone samples were clamped in a Mark-10 Tensile Tester (Mark-10, Copiague, NY) and aligned with a laser level, as shown in Fig. 1B. The Mark-10 Series 5 digital force gauge has a range from 0.5 N to 10,000 N. A tensile load of either 0.5 N or 5 N was applied and the sample was then preconditioned for 5 cycles, ramping between 0 % and 10 % strain at a rate of 10 mm/min, following ASTM guidelines. Minimum and maximum preconditioning forces and the number of dog-bone samples tested for each condition are listed in Table 1. After completion of the preconditioning, each sample was extended to failure by ramping at 1100 mm/min, the maximum velocity achievable with the Mark-10 tensile tester. Force and length were sampled at 50 Hz. All tests were conducted at room temperature.

2.2. Impact Force Protocol

Drop tower tests were performed to determine the forces necessary to produce laceration of the synthetic skin and to quantify the extent to which the viscoelastic properties of SynTissue® modified the impact forces experienced by the underlying material, as would be expected with human skin. A block of kiln-dried 2 ×4 wood was placed on a custom aluminum force plate and a SynTisssue® 8 N plate was arranged on the wood at the bottom of a drop tower. A steel crowbar was clamped to the sliding carriage of the drop tower and allowed to drop onto the SynTissue® as illustrated in Fig. 2. Only the portion of the SynTissue® plate being tested was exposed. The remainder of the plate was kept in its plastic wrapping to preserve its moisture content. The crowbar had a mass of 1.155 kg and length of 59 cm. It had a hexagonal cross-section with a width of 1.7 cm. Impact force was varied by dropping the crowbar from heights of 2.4 cm, 13.9 cm, 19.4 cm, 23.5 cm, 29.2 cm, 39.5 cm and 50.3 cm above the wooden block in order to achieve a range of impact forces that spanned the region for which lacerations were observed for cadaver scalp and porcine head. The tests were repeated without the intervening SynTissue®, dropping the crowbar directly onto the wood. Three trials were conducted at each drop height. The impact force was measured using a custom aluminum force plate which incorporated four calibrated piezoelectric force sensors (PCB Piezotronics), each with a range from 0 to 35,000 N. The force was sampled at 10 kHz. A photograph was taken of each SynTissue® plate following impact to determine whether the material had been lacerated.

2.3. Elastic modulus analysis

The force recorded during extension of the dog-bone samples was converted to stress by dividing the force by the nominal cross-sectional area (width x thickness) at the center of the dog-bone at its rest length. The strain was calculated by dividing the length of sample during extension, by its rest length. The stress generally increased in a relatively linear manner with strain as illustrated in Fig. 3A. However, in two cases for the SynTissue® 2 N, the stress increased in a curvilinear manner, as illustrated in Fig. 3B. The elastic modulus was estimated by selecting two points in the linear region of the stress vs strain relation and dividing the change in stress by the change in strain.

Table 1
Minimum and maximum forces of the ramp cycle.

Test Material	Number of Samples	Dog-bone Width (mm)	Force Range (N)
SynTissue® 2 N	4	6	0.5–1.0
SynTissue® 2 N	4	3.18	0.5–0.85
SynTissue® 4 N	4	6	0.5–2.15
SynTissue® 4 N	4	3.18	0.5–1.6
SynTissue® 8 N	1	6	0.5–17.1
SynTissue® 8 N	7	6	5–15
SynTissue® 8 N	1	3.18	0.5–8.6
SynTissue® 8 N	4	3.18	0.5–7.5

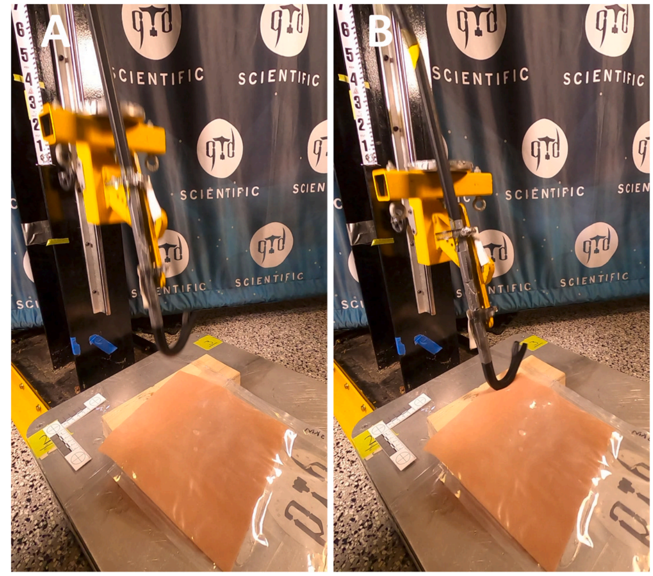

Fig. 2. A. Drop tower setup showing a trial in which a SynTissue®plate was placed over the wooden block, showing downward movement of the crowbar. The plastic wrapping seen in the photos was peeled back to expose a new section of SynTissue® for each impact test. B. The same trial showing the instant of crowbar impact with the SynTissue® plate.

2.4. Impact force analysis

The peak impact force was determined for each trial as shown in Fig. 4 and the mean peak force of the three trials for each drop height was compared for the trials with and without the SynTissue® by performing a paired t-test to determine whether the SynTissue® attenuated the peak force.

3. Results

3.1. Elastic modulus

Table 2 lists the elastic modulus for each test. The mean elastic modulus for the SynTissue® 2 N dog-bone samples was 0.668 MPa (SD 0.418), the mean elastic modulus for the SynTissue® 4 N dog-bone samples was 5.01 MPa (SD 0.62) and the mean elastic modulus for the SynTissue® 8 N dog-bone samples was 14.9 MPa (SD 5.2).

3.2. Impact force

Table 3 lists the peak impact force measured for each drop height when the crowbar was dropped onto the wood and when it was dropped onto the SynTissue® plate covering the wood. From the paired t-test it was determined that the peak force was significantly lower for the condition where the SynTissue® covered the wood than for the condition with the wood only ($p < 0.0001$). Dropping the crowbar from a height of 2.4 cm produced plastic deformation of the SynTissue® in the form of an impact crater, but did not appear to lacerate the material, as seen in Fig. 5A. The first evidence of laceration occurred for a drop of 13.9 cm with a peak force of 2177 N, although peak forces below 3406 N did not consistently produce lacerations (Table 3). As illustrated in Fig. 5B, for forces of 3406 N and greater there was a clearly visible

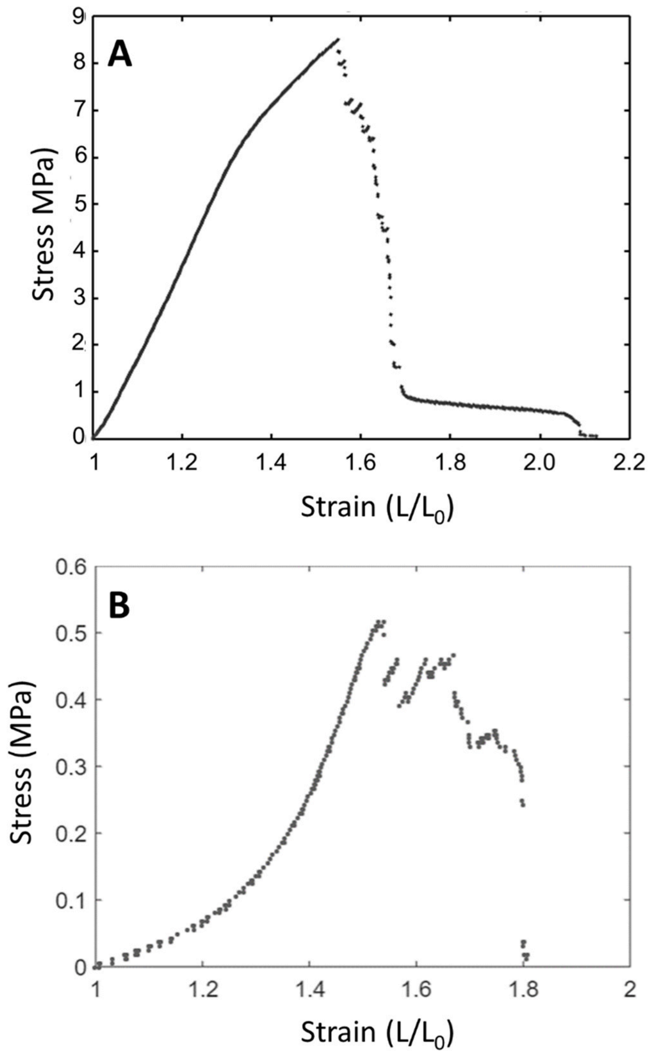

Fig. 3. A. Stress vs strain curve for a trial with a SynTissue® 8 N dog-bone sample. B. Stress vs strain curve for a trial with a SynTissue® 2 N dog-bone sample.

white line in the impact crater which suggests that the impact severed the synthetic skin to its fiber base.

4. Discussion

Surrogates for human skin are being used as a tool in forensic investigations where injuries to the skin are used to estimate impact force in blunt trauma, as well as providing a realistic surface layer for surrogate anatomical models used to simulate injuries to bone or underlying soft tissue [12,17,2,8]. SynTissue® is a synthetic material designed to mimic specific mechanical properties of the skin such as penetration force. Our tests were designed to determine whether SynTissue® could mimic other mechanical properties of the human scalp, namely its elastic modulus and laceration force threshold. In addition, we investigated its capacity to attenuate impact force.

The elastic moduli for all of the SynTissue® 2 N and 4 N dog-bone samples were well below the range measured for human scalp samples whereas the elastic moduli for 7 of the 12 SynTissue® 8 N dog-bone

Table 2
Elastic modulus.

Test Material	Force Range (N)	Elastic Modulus (MPa)
SynTissue® 2 N	0.5–1.0	1.51
SynTissue® 2 N	0.5–1.0	0.63
SynTissue® 2 N	0.5–1.0	0.73
SynTissue® 2 N	0.5–1.0	0.57
SynTissue® 2 N	0.50–0.85	0.80
SynTissue® 2 N	0.50–0.85	0.08
SynTissue® 2 N	0.50–0.85	0.31
SynTissue® 2 N	0.50–0.85	0.71
SynTissue® 4 N	0.50–2.15	4.48
SynTissue® 4 N	0.50–2.15	5.43
SynTissue® 4 N	0.50–2.15	5.02
SynTissue® 4 N	0.50–2.15	6.05
SynTissue® 4 N	0.5–1.6	5.40
SynTissue® 4 N	0.5–1.6	4.25
SynTissue® 4 N	0.5–1.6	4.36
SynTissue® 4 N	0.5–1.6	5.11
SynTissue® 8 N	0.5–17.1	16.1
SynTissue® 8 N	5–15	15.7
SynTissue® 8 N	5–15	23.1
SynTissue® 8 N	5–15	20.5
SynTissue® 8 N	5–15	10.6
SynTissue® 8 N	5–15	15.1
SynTissue® 8 N	5–15	20.4
SynTissue® 8 N	5–15	18.8
SynTissue® 8 N	0.5–8.6	11.7
SynTissue® 8 N	0.5–7.5	7.78
SynTissue® 8 N	0.5–7.5	13.1
SynTissue® 8 N	0.5–7.5	6.48

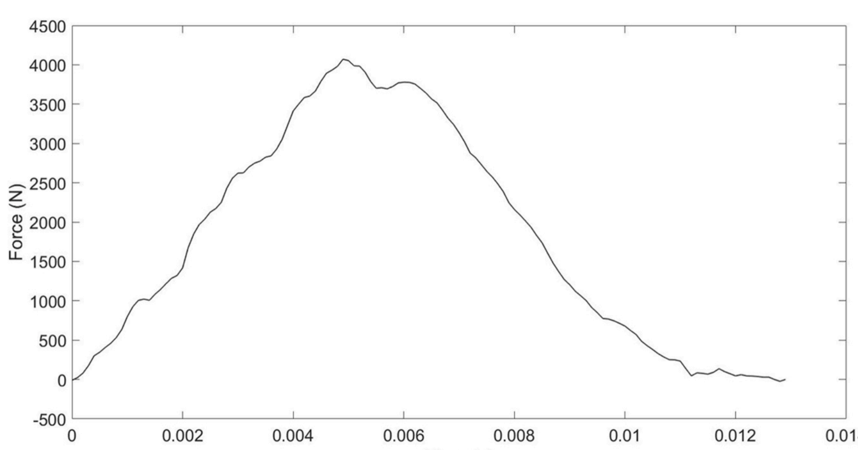

Fig. 4. Impact force profile for a trial in which the crowbar was dropped from a height of 50.3 cm onto a SynTissue® 8 N plate.

Table 3
Impact force.

Drop Height (cm)	Peak Force Wood (N)	Peak Force SynTissue® (N)	Laceration
2.4	966	886	No
2.4	971	876	No
2.4	1015	802	No
13.9	2096	2194	No
13.9	2340	2177	Yes
13.9	2368	2135	No
19.4	2651	2235	No
19.4	2669	2329	No
19.4	2500	2407	No
23.5	2822	2638	Yes
23.5	2813	2794	No
23.5	2816	2710	No
29.2	3167	2818	No
29.2	3150	2627	No
29.2	2828	2800	Yes
39.5	3692	3406	Yes
39.5	3820	3408	Yes
39.5	3698	3283	Yes
50.3	4526	4074	Yes
50.3	4644	4321	Yes
50.3	4558	4289	Yes

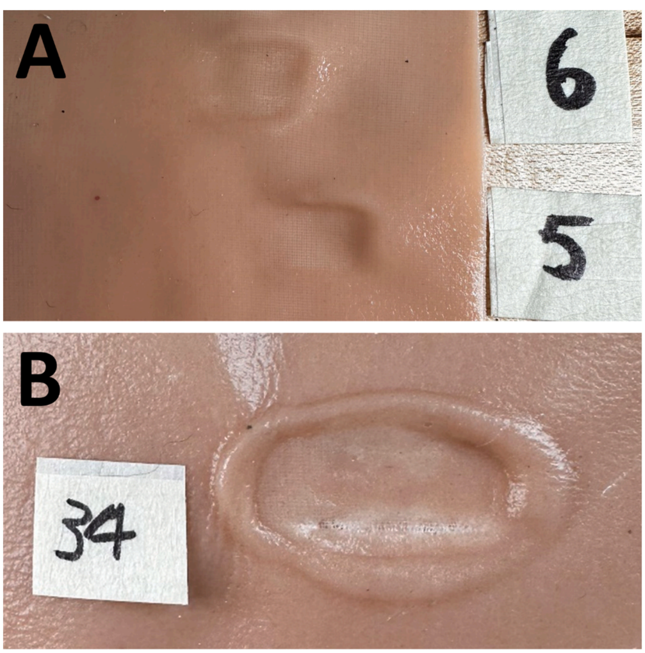

Fig. 5. A. Deformations of a SynTissue® 8 N plate when the crowbar was dropped from a height of 2.4 cm. B. Deformation of a SynTissue® 8 N plate when the crowbar was dropped from a height of 39.5 cm. The white line visible near the lower edge of the deformation represents the natural fiber base of the SynTissue® plate. The appearance of the fibers is interpreted to be analogous to a skin laceration.

samples fell nicely within the range measured for human scalp samples. We found that the mean elastic modulus of SynTissue® 8 N was comparable to that of the human scalp [4–7,16]. Furthermore, the stress vs strain relation for SynTissue® 8 N, shown in Fig. 3A, is very similar to the stress vs strain relations depicted in previously published studies [16,4,7]. Thus, SynTissue® 8 N would be a suitable surrogate for the human scalp in forensic investigations where tensile properties of the scalp are critical.

Deformation of SynTissue® 8 N, interpreted as being equivalent to a scalp laceration, occurred for peak forces as low as 2177 N and consistently for peak forces equal to or greater than 3406 N, which is in the range reported for the scalp of human cadaver heads [9] although less than 4149 N reported for porcine head tissue (Sharkey et al., 2012). It should be noted that Sharkey et al. [14] only examined only a single impact force less than 4149 N so it is possible that lacerations of porcine head tissue could occur at impact forces lower than those tested. Furthermore, it is possible that lacerations of the human scalp may occur for impact forces that are different than for porcine head skin given that penetration forces may differ between human and porcine skin [1] in addition to differences in skin contour. Nevertheless, the results suggest that the minimum blunt impact force required to "lacerate" SynTissue® 8 N is relatively similar to the blunt impact force required to lacerate both the human scalp and porcine head tissue, although the occurrence of a laceration may depend on other factors.

There is one feature of the deformation of the SynTissue® following impact with a blunt object, which is definitely inconsistent with human scalp mechanics, namely the plastic nature of the deformation. The contact region by the blunt object created a permanent crater resembling the cross-section of the crowbar. In contrast, the elasticity of the scalp allows it to recover its original shape following impact. This difference suggests that SynTissue® is more viscous than human skin. This plastic deformation, may, nevertheless, serve a useful purpose. SynTissue® retains the shape of the blunt object, allowing deformation patterns of different blunt objects to be compared. Although human skin may recover it shape after blunt object impact, abrasions or contusions caused by the impact would remain visible. Their shape could be compared to the shape of the SynTissue® deformation produced by different blunt objects to distinguish between different possible objects responsible for the trauma.

In summary, SynTissue® cannot be considered as a realistic substitute for human scalp, despite extensive application in medical training. Its mechanical behavior in cross-sectional compression differs significantly from that of human or porcine scalp. Human skin surrogate materials should exhibit similar deformation and restitution properties to human skin. Nevertheless, SynTissue® does exhibit some features which could be useful for forensic investigation. Future research into surrogate materials for human skin should include characterization of elastic, viscous and plastic properties in all three dimensions for comparison with human or porcine skin.

Declaration of Competing Interest

None.

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