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Fantastic plastic? Experimental evaluation of polyurethane bone substitutes as proxies for human bone in trauma simulations

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ABSTRACT

Recent years have seen steady improvements in the recognition and interpretation of violence related injuries in human skeletal remains. Such work has at times benefited from the involvement of biological anthropologists in forensic casework and has often relied upon comparison of documented examples with trauma observed in skeletal remains. In cases where no such example exists investigators must turn to experimentation. The selection of experimental samples is problematic as animal proxies may be too dissimilar to humans and human cadavers may be undesirable for a raft of reasons. The current article examines a third alternative in the form of polyurethane plates and spheres marketed as viable proxies for human bone in ballistic experiments. Through subjecting these samples to a range of impacts from both modern and archaic missile weapons it was established that such material generally responds similarly to bone on a broad, macroscopic scale but when examined in closer detail exhibits a range of dissimilarities that call for caution in extrapolating such results to real bone.

1. Introduction

In cases involving the analysis of skeletal remains biological anthropologists can often provide unique contributions to assist the pathologist and law enforcement agencies. One such area is in the recognition of injuries to bone where investigations of past conflict through analysis of archaeological burials have brought particular focus to injuries caused through violence. Such work generally relies on comparisons with documented injuries. In the case of more obscure or unusual mechanisms of injury, or when looking at past populations a known comparator may not be available, for example in the case of archaic weapons that are no longer in use. The best option to resolve uncertainty in such cases is through actualistic experiments.

Experimentation in controlled circumstances is attractive, but raises questions regarding suitable test samples. In simulating skeletal trauma human cadaveric samples will obviously produce results that are very close to those that would be expected in a living individual but are not necessarily the most desirable option. Human cadavers are often difficult to obtain, carry infection risks and have issues of variability between samples. Aside from these points using human remains for such work is fraught with ethical concerns and often legal complications that rule them out for many researchers. Bone from non-human animals is a promising alternative, but is complicated in respect of anatomical differences between humans and other species. With regard to some parts of the skeleton such as ribs or flat bones such as the scapula, the overall form of some mammalian bones may be sufficiently similar to humans to make these a reasonable proxy. However, the unique size and form of the human cranium remains an intractable problem as non-human crania are so different in size, shape and thickness that results obtained from them are of limited value. This point has particular relevance to trauma as the head is a common target in assaults and is also the part of the skeleton where patterns of injury are most easily recognised.

A potential alternative is presented by the commercial availability of synthetic bone substitutes formed from polyurethane. These products offer several immediate advantages over human cadavers or non-human animal bone. They can be obtained quickly in variable quantities, each specimen is identical and they avoid complications of legality, ethics and infection. It would therefore seem that such material would be an obvious choice, however, this

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point hinges on the extent to which these replicas respond to dynamic impacts in ways that are analogous to real bone. In a series of papers Thali et al. [1–4] claimed that similar replicas produced results that were highly accurate with regard to ballistic and blunt-force trauma, although these studies concentrated largely on simulated soft tissue at bullet entrance and exit points and the general appearance of fracture patterns at a gross scale. Thali et al. [1–4] focused on a small range of modern firearms and a mechanism of blunt trauma, if such samples are viable substitutes for human crania they should hold equal potential for investigations of other mechanisms of injury.

The current paper presents a pilot study designed to test this issue using a range of projectiles and mechanisms of launching them. Polyurethane bone substitute (PBS) samples were impacted with high, medium and low velocity projectiles shot using three different classes of modern and archaic weapons. The resultant defects in the samples were examined both grossly and in detail in order to assess the extent to which they resembled those produced in experimental animal bone samples and published examples of bony trauma in humans.

2. Materials and methods

2.1. Polyurethane bone substitute (PBS)

The synthetic bone samples tested in the current study were obtained from Synbone AG (Malans, Switzerland) [5]. These products are marketed primarily as anatomical models for surgical training. The manufacturers do not give specific details about the composition of these products but describe them as being made of "specially formulated polyurethane foam" which have "in some instances the mechanical properties of natural bone" [5]. In addition to replicas of individual bones and particular portions of the skeleton for practicing surgical techniques, the suppliers also offer generic geometric forms for ballistic tests. These latter are supplied as flat plates, and hollow cylinders and spheres, representing flat bones, generalised long bones and crania respectively. The samples used in the current study were purchased by the first author's institution at the standard commercial rate.

2.2. Testing low, medium and high velocity impacts

The responses to impact of both flat plates and spheres of PBS were tested by firing shots at them using three different weapon types, modern rifles, a black powder musket and a crossbow. These weapons deliver differently constructed projectiles with stark differences in velocity and discharge energy (Table 1). The modern rifles were firstly a 7.62 mm Parker Hale T4 target rifle discharging a 7.62 × 51 mm NATO Full Metal Jacket (FMJ) bullet, a military round common internationally (Pretoria Metal Pressings, South Africa). The second was a Tikka model 550 rifle firing a .243″ 100 grain Winchester Soft Point bullet, generally used for sport and hunting (Prvi Partizan, Serbia). The black powder musket was a replica 1861 model .58 calibre carbine discharging solid lead minié balls measuring (13.5 mm diameter). The crossbow was a Jaguar 175 lb recurve crossbow loaded with 17 ¼ inch long Perfectline alloy bolts fitted with conical target heads (8.0 mm diameter).

2.3. Experimental conditions and samples

To comply with local police health and safety requirements the samples were shot in a prepared pit 1.5 m deep. The bottom 0.8 m of fill consisted of sieved sand to reduce risk of ricochet. The weapons were fired from a very close range of approximately 2 m, secured in a fixed cradle to facilitate aiming and repeatability, at an angle of 65° (Fig. 1.). Shots were fired into flat PBS plates (5 mm thick) and also PBS spheres of both 5 mm and 7 mm thickness. The latter are formed of two hemispheres held together with adhesive, with the consequent junction between the halves mimicking cranial sutures in a simplified form. The spheres also have an opening at the base which broadly simulates the openings in the cranium, particularly the foramen magnum. The work detailed in the current paper is part of a wider suite of ballistic experiments with relevance to Forensic Anthropology. One of these parallel projects [6] utilised cattle (*Bos taurus*) scapulae as proxies for human cranial bone in considering microscopic effects of gunshot trauma. Here fresh scapulae obtained from an abattoir from animals that had been slaughtered for food, were shot with minimal soft tissue (<5 mm thick) adhering. The soft tissue was then removed using enzymatic detergent to allow examination of damage to the bone. These bovine samples also offered a useful comparison with aspects of the PBS samples in the current study as they were shot at the same time using the same weapons. Other studies have shown that areas of flat bone in large mammals respond in a uniform manner to ballistic trauma and so can be taken as a reasonable proxy for cranial and other flat bones in humans [7,8] -although they do not exhibit the kind of additional fractures that derive from the enclosed form of the cranial vault (see below).

2.4. Simulating brain and associated soft tissue

Initial tests were conducted firing the modern rifles into flat PBS plates and empty spheres to assess whether the different shapes would affect the way the material responded to impacts. In fact there were no gross differences between the two. Both exhibited simple 'internally bevelled' defects resembling those seen in gunshot injuries to areas of flat bone -i.e. where the internal/endocranial dimensions of the defect are larger than its external/ectocranial dimensions [9–15]. However, the damage produced in the PBS spheres differed from gunshot wounds in real crania as there were no secondary or tertiary fractures of the kind frequently seen in cases of such trauma (see below). It was hypothesised that the lack of such fractures was related to the absence of soft tissue (brain, dura, etc.) inside these artificial 'crania'. Such soft tissues inside the cranium present a soft, semi fluid medium through which a hydraulic shockwave will form transmitting the kinetic energy of an impact to the cranial walls producing characteristic fractures [16]. In subsequent tests the spheres were therefore filled with ballistic gelatin (constituted at 10% by weight at 4 °C). This

Table 1
Characteristics of the weapons and ammunition used in the experiments. Velocity data derived from: *Manufacturers website; **Measured by present authors by chronograph; ***Averaged from published velocities for four black powder weapons of similar type and date [44].

Weapon	Ammunition				Velocity (m/s)	Energy (J)
	Type	Calibre	Weight [grains]	Weight (grams)		
Tikka 550	Winchester SP	.243″	100	6.5	905*	2660
Parker Hale T4	Nato FMJ	7.62	147	9.5	853**	3456
1861 Carbine	Minie Ball	0.58	463	30.0	468***	3285
Jaguar Crossbow	Perfectline alloy	8.0	363	23.5	75*	66