Comparing the use of meat and clay during cutting and projectile research

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Abstract

Diverse disciplines investigate how muscular tissue (i.e. ‘meat’) responds to being cut and deformed, however, large-scale, empirically robust investigations into these matters are often impractical and expensive. Previous research has used clay as an alternative to meat. To establish whether clay is a reliable proxy for meat, we directly compare the two materials via a series of cutting and projectile tests. Results confirm that the two materials display distinct cutting mechanics, resistance to penetration and are not comparable. Under certain conditions clay can be used as an alternative to meat, although distinctions between the two may lead to experimental limitations.

Keywords: Force; Fracture; Stone Tool; Material Science; Butchery

1. Introduction

A diverse range of disciplines investigate how muscular tissue (i.e. 'meat') responds to being cut and deformed under different experimental conditions. Animal products are primarily used in these studies, either as a substitute for human tissue, or when addressing questions relating to the butchery and processing of animal products in 'real-world' settings. Of note are ergonomic investigations examining how different cutting tools influence musculoskeletal stresses when processing animal carcasses within industrial settings, engineering and medical research investigating how cutting mechanics and tool use capabilities are influenced by varying cutting edge forms, and archaeological research interested in the relative ability of different artefact types and forms to be used during hunting and butchery activities.

The work of McGorry and colleagues are prominent examples from an ergonomic perspective [1]; [2]. In a series of publications examining the implications of blade sharpness, edge angle, and finish on grip forces and moments during modern industrial butchery settings, participants undertook the butchery of beef and lamb in diverse ways (e.g. shoulder boning, intercostal trimming, Y-cutting, shoulder fleecing) and on a relatively large scale (21 participants performed the shoulder fleecing and Y-cutting, for example). Szabo et al [3] published similar experiments examining industrial poultry processing. Mechanical and medical engineering research has also examined how aspects of tool-form variation influence their ability to cut biological tissue, but instead often focus on how these variables influence their respective fracture mechanics. Shergold and Fleck [4], for example, used pigskin samples alongside in vivo tests on human skin when examining the relative performance (crack geometry) of sharp and flat-bottomed punches and hypodermic needles. Kasiri et al [5] utilised bovine bones when measuring indentation and failure in cortical bone when cut with a surgical blade. Others have utilised processed meat foodstuffs when investigating the cutting mechanics of associated implements (e.g. wire band saw) in industrial or food preparation settings [6]; [7].

Archaeological research has heavily employed experiments that process animal tissues within two research themes. First, numerous publications that have sought to replicate past butchery activities when investigating the relative ability of different tool forms to undertake butchery processes, examinations into the formation of cut marks on bones, and the processes leading to the development of microwear traces (e.g. [8]; [9]; [10]; [11]; [12]; [13]; [14]). Just as prominently, archaeologists have also long been concerned with the projectile technologies of past populations and have frequently undertaken replication experiments investigating form-function relationships and damage formation processes to both tools and targets (e.g. [15]; [16]; [17]; [18]). It is notable that Palaeolithic archaeology has a particular emphasis upon such experimentation [19].

All fields, however, face issues when using substantial quantities of animal materials in laboratory based experiments. These issues include the expenses of responsibly acquiring and safely disposing of animal tissues; a need for cold storage facilities; relevant health and safety concerns when processing and storing animal products; and the ethical concerns of utilising animal products. While these issues may be somewhat abated in studies of limited scale, they can pose substantial hurdles to large-scale quantitative studies. Further, differences and inconsistencies within animal tissues (muscle fibres, fat, connective tissue etc.) and between carcasses (size, muscle depth, time since death, etc.) may pose problems to studies of cutting mechanics at the micro-scale and comparisons between experimental subjects, respectfully. These concerns have previously been identified by researchers (e.g. [20]) and, at times, led to the use of industrially produced materials as animal product proxies in cutting and projectile experiments. Iovita et al. [21] and Wilkins et al. [22], for example, recently utilised ballistics gelatine instead of animal tissues when examining the functionality of stone tipped weaponry. Similarly, Key, Lycett and colleagues utilised neoprene rubber, polypropylene rope, polythene sheeting, and double-walled corrugated cardboard when testing the relative cutting capabilities of different stone tool forms [23]; [24]; [25]. While such materials may successfully examine the influence of external variables on tool-use capabilities, there are likely key differences in the resistance provided to cutting edges and how fractures initiate in these materials. Certainly, ballistics gelatine has demonstrated differences in the depth of penetration of projectiles and nature of the damage produced when compared to both pig and simulated thoraxes [26]; [27]. Moreover, cardboard and rope display distinct constitutive forms to bio-materials and do not display the typically J-shaped stress-strain curve of meat [28]. So, while such materials are useful and, dependent upon the hypotheses being investigated, are often suitable to be used as a standardised material to be cut, it would be useful to identify an alternative material that negated the above-mentioned problems and displayed similar resistance and fracturing properties to animal tissues.

Consequently, past research has both utilised materials that were thought to replicate the cutting mechanics of animal materials, and has directly tested their comparability against animal tissues. McCarthy et al. [29] and Schuldt et al. [7], for example, previously used polyurethane and ethylene propylene diene monomer rubber sheets (respectfully) when examining relationships between sharpness and cutting forces in metallic blades as these materials are considered to display similar fracture mechanics to animal tissues and other similar bio-materials. Marsot et al. [30], on the other hand, compared the shear strength of meat against a series of synthetic materials, and identified a relatively dense polyolefin-based foam as displaying both similar shear strength and cutting forces to meat. Shergold and Fleck [4: 841] went into much greater detail when outlining why silicone rubber may be considered as an “approximate substitute for human skin”, providing a detailed review of the mechanical properties of both materials when being cut. Kalcioglu et al. [31] similarly examined the mechanical behaviours of animal tissues and industrially produced materials, but in this instance compared the penetrability, energy dissipation, and deformation mechanics of heart and liver tissues against a series of tissue simulant gels in projectile tests. Their results indicated that even the best simulant gel still exceeded the penetration depths of the animal tissues by at least ~15%.

As suggested by McGorry et al. [20]; [32], clay may also provide a suitable alternative to animal tissues during cutting experiments. In a study examining how task station and blade orientation variation influences gripping forces, cutting moments, and upper limb kinematics during a cutting task using a knife, they suggested that modelling clay provided cutting moments similar to “sirloin and London broil cuts of beef” [20: 1644]. Others have utilised clay during controlled ballistics and cutting experiments when recording penetration levels when protected by different body armour fabrics [33] and deformation and failure rates in clay substrate when cut with tines [34] (although neither used clay as a direct proxy for biological tissues). While clay may intuitively appear similar meat in several important ways (e.g. resistance to a cutting edge), they represent two materials with very distinct compositions, with meat being a fibrous organic tissue and clay primarily being formed of silicate particles and trapped water. Moreover, there has yet to be a controlled experimental investigation specifically addressing the relative ability of clay to provide an accurate alternative to meat.

Here we redress this issue and assess the suitability of fresh potters clay to be used as an alternative to meat during cutting and projectile activities. Specifically, we undertake two rounds of experiments. The first examines the forces and deformation required to cut clay and meat of equal measure with a straight, homogeneous metallic blade. The second examines the ability of modern metallic composite arrows and Palaeolithic stone projectiles to penetrate clay and meat when fired at a controlled speed and distance. We conclude by discussing the nature of any similarities or differences in the two materials and the suitability of using clay as a substitute to meat in future archaeological, ergonomic, and engineering experiments.

2. Loading Rates during Cutting

The relative ability of sharp edged tools to initiate fractures in materials and permanently separate two or more of their aspects is of broad importance to many areas of research (see Atkins [2009] and examples therein). Consequently, examinations into the forces required to cut materials with metal knives, stone tools, and other implements have taken many forms, including the use of pressure sensitive pads attached to the hands, force sensors beneath worked materials, and finite element modelling (e.g. [1]; [35]; [36]). Here we use an approach widely used within fracture mechanics research [7]; [29]; [37].

Forces and deformation levels during cutting were recorded here using an Instron® 5500 universal tensile testing system (Fig. 1). We used 30 steel 2-facet utility (razor) blades (Kolbalt®) during the cutting tests, all of which were secured into 70x38x18 mm wooden blocks. Each blade was fixed into a block such that only 24mm of cutting edge remained exposed (Fig. 1). The blocks were secured into the upper grip of the testing machine and each blade was used to cut both materials (Fig. 1). The clay was low-fire potters clay bought from Standard Ceramic Supply Company (Pittsburgh, USA) and the meat (beef) was chosen to contain limited intramuscular fat or connective tissue. Tissue fibre direction was not controlled in the meat. All blades cut the clay first and then the meat. 20 mm thick portions of each material were placed on a secure wooden platform beneath the grip (the latter material required additional securing with coarse sandpaper at its base to prevent movement during cutting). There was slight variation in the thickness of the meat due to it deforming and flexing when being cut into portions. The wooden platform was aligned so that only 20 mm of each material was beneath the blade's exposed edge. Beneath the portion of material being cut there was a 5mm gap in the wooden platform, into which the blade entered as it cut through the material.

The crosshead, into which the grip and blades were fixed, was lowered prior to the test so that the tip of the blade's edge was in contact with the material surface (but applying no pressure). At this point the displacement reading was set to zero. The blades were lowered into each material at a rate of 20 mm/min. Displacement (mm) and force (N) levels were recorded for each controlled cut, which continued until the blade passed through the material in its entirety. Two sampling frequencies were used in each test. The first 7mm of deformation was recorded at a rate of 10 Hz, after which the sampling frequency dropped to 2 Hz. This allowed a greater level of detail to be recorded at the point of cut initiation and/or initial material deformation.

3. Penetrability during Projectile Use

The aim of our second test was to investigate the resistance provided by clay and meat targets when struck by projectile points. We investigated this by comparing the depth of penetration achieved by modern metal composite arrows and Palaeolithic replica stone points when fired from a standardised distance, angle, and speed. If each material returned similar penetration distances and levels of variation, then it may be suggested that clay could be a suitable alternative to meat within studies of projectile weaponry. Penetration depths were recorded from 204 composite arrow shots, being fired into the clay and meat 102 time each. Similarly, penetration depths were recorded from 60 replica stone point shots, striking the meat and clay 30 times each. Following this, we used high-speed video to analyse three-dimensional (3D) projectile impact dynamics (i.e., ballistics) of an additional 19 shots fired into meat and 18 shots fired into clay.

The clay target was formed of 45.4 kg of material and was shaped into an orthorhombic cuboid measuring 22x25x45 cm^3 (Fig. 2). As in the cutting experiment, the clay was low-fire potters clay bought from Standard Ceramic Supply Company (Pittsburgh, USA). In all instances during shaping the clay was compressed (wedged) to ensure no pockets of air were present. Due to the differential size of the projectiles, this was repeated after every 20 shots for the arrows and every 10 shots for the stone points. The meat target was formed from 12.7 kg of beef rump that did not contain any bone or skin. Intramuscular fat and connective tissue was, again, minimal. Six 'rump roasts' were lined up to form a target 45 cm deep, before being surrounded on five sides by a ~5 cm clay wrap (Figs. 2E and 2F). The clay 'wrap' was pulled taught, such that it enveloped the beef and provided resistance to its edges. The beef was replaced every 30 shots for the arrows and every 5 shots for the stone points. Both materials were supported on a wooden platform 1 m from the floor and 3.5 m from the tip of the projectiles at the point of release (Fig. 2). At the point of release the projectiles were 125 cm from the ground and, therefore, aligned with the top of the clay target. Projectiles were, however, aimed at the centre of the clay, meaning that there was a very slight slope at the point of entry. Data was only collected from the clay when the projectiles entered more than 5cm from its edge (Fig. 2D). Due to the clay surrounding the meat, all shots that were on target for this material were counted, so long as no clay was struck. Data were only ever collected from projectiles that impacted on portions of material that maintained surface integrity and had not been hit by previous shots.

75 cm long Easton (XX75 Tribute 1616) metal alloy arrows weighing 20.6 g and with diameter of 6 mm were used as the composite arrow (Fig. 3). The stone tipped projectiles (Fig 3) were lanceolate points made from Texas chert (Fredericksburg variety), produced by C. Ratzat (www.neolithics.com). All stone points used were similar in morphology, having been ground into the following form using modern lapidary equipment: 76.2 mm length; 27.94 mm medial width; and 7.94 mm medial thickness, with the thickness tapering toward the point's tip, base, and lateral edges. The stone points were then hafted by R. Berg (www.thunderbirdatlatl.com) on one-meter long shafts of air-dried ash wood, which is extremely resilient and resistant to bending and breakage (Berg, personal communication). The diameter of each shaft was approximately 10.25 mm. The adhesive used for the hafting was heated bone glue, which was specifically developed by Berg. The material used for the lashings was an animal-based silk fibre from bovines.

Both the arrows and the stone tipped projectiles were fired from a 29 lbs compound bow fixed to an automatic compound bow stand (Spot-Hogg 'Hooter Shooter'), allowing for precision shooting at predefined draw lengths and velocities. All arrows were fired at a target speed of 30.5 meters per second (m/s), whereas the stone points were fired at a target speed of 25 m/s. Limited variation was to be expected in each case due to the ratcheting system used to draw the bow, minute differences in arrow notch contact with the drawstring, and negligible deviations in projectile trajectory. All projectiles were fired through a Shooting Chrony chronograph, allowing their precise speed to be recorded as it passed through the two aspects of its triangular frame, activating photo-resistors set at a known distance from one another. Depth of penetration was recorded for both projectile types in millimetres (mm) and was measured from the tip of the arrow's point to the first aspect of the shaft that remained outside of the target material.

We used two synchronised high-speed cameras (Fastec HiSpec Lite cameras, Fastec Imaging, San Diego, CA USA) to quantify the dynamics of how each projectile impacted the two different materials. The cameras were operated at a frame rate of 800 Hz, shuttered at a rate of 8000 Hz (i.e., exposure duration of 0.125 ms) to minimise motion blur, and synchronised by means of a common push button trigger. Prior to each experiment, we affixed a series of six bands of retro-reflective tape (Scotchlite Brand, 3M Corporation, St. Paul, MN USA) along the shaft of each arrow to provide high-contrast features for subsequent digitising of projectile motion (Fig. 2F). We calibrated the two-dimensional images from each camera to a common 3D coordinate frame following the methods of Theriault et al [38], using their freely available "easyWand" toolbox for MATLAB (MathWorks Inc., Natick, MA USA). Briefly, we calibrated a volume approximately 1 m by 1 m by 0.5 m immediately surrounding the projectile target using the Sparse Bundle Adjustment (SBA) algorithms in the easyWand toolbox. The program takes as input the digitised x,y pixel position of "background" points visible to both cameras (i.e., any discrete feature identifiable in the volume of interest). An object of known length – the "wand" – is also filmed moving through the volume to transform image dimensions into real-world units (i.e., meters) and to provide additional reference features for the SBA calibration. The SBA algorithm combines the apparent planar position of all of these features with data on intrinsic parameters of the cameras (e.g., lens focal length, radial distortion properties of the lenses, camera sensor size, and principal focal point on the sensor) to generate a set of Direct Linear Transformation (DLT) coefficients that precisely describe the position of each camera in space [39]. Using these calibrations, we were able to localise the 3D position of moving projectiles with an accuracy of 1.75-2.5 mm. Finally, we entered the DLT coefficients into the DLTdv5 motion-tracking toolbox for MATLAB [40], and used this software to digitise the 3D x,y,z position of the reflective markers spaced along each projectile's shaft during the period of impact.

4. Data Analysis

4.1 Cutting

Loading (N) and blade displacement (mm) were recorded during each cutting test. In turn, it was possible to visualise load-displacement curves during each cut and material stiffness (calculated from the slope between adjacent data points after smoothing [N/mm]) relative to blade displacement. Shapiro-Wilk tests confirmed that although the maximum loading levels for both materials and the mean loading levels for the clay were normally distributed ($p = .162-.803$), the mean loading levels required to cut the meat were not ($p = .005$). Hence, Mann-Whitney U tests ($\alpha = .05$) were used to statistically compare the maximum and mean loads recorded in the cutting tests of the two materials. Maximum loads were defined as the greatest load recorded at any point during the cutting test. Mean loads were calculated from the point at which data collection started up until the blade had fully emerged through the portion of material (i.e. displacement = 39 mm). Only one in every five data points for the first 7mm of cutting was utilised for the calculation of mean load (so that all data in this measure was equivalent to a sampling rate of 2 Hz). Differences in the load-displacement curves and stiffness plots of the two materials are also compared.

4.2. Projectiles

Projectile speed and depth of material penetration was recorded for both the metal arrows (n = 102) and stone points (n = 30) in each of the two materials. Shapiro-Wilk tests identified the penetration depths of both projectiles during the meat test to be normally distributed (p = .498 and .766 for the arrow and stone point, respectively). Whereas the stone point clay data was normally distributed (p = .610), the penetration depths returned for the arrow when fired into the clay was not (p = .010). Hence, we used non-parametric aligned rank-transformed analyses of variance (ANOVAs) to analyse these data [41]. Aligned rank-transformed ANOVA is a non-parametric alternative to a standard parametric two-way ANOVA that permits testing of both main effects and interactions in a full-factorial design. In the case of significant interactions, Mann-Whitney U tests were used for post-hoc analyses of within cell differences (i.e., differences between responses to different material types within a given projectile type). P-values for post-hoc tests were adjusted using the False Discovery Rate procedure [42] to control for experiment-wise Type I error inflation.

The dynamics of projectile impacts (i.e., impact ballistics) were analysed from motion-tracked video data using a custom-written MATLAB program. We first fit raw x, y, z coordinate data to a quintic smoothing spline (i.e., MATLAB's SPAPS function, set to a tolerance of 10^{-5} mm^2), providing a parameterised function describing instantaneous projectile displacement with respect to time. Instantaneous projectile velocity was subsequently calculated as the first derivative of the smoothing spline. Instantaneous fore-aft (i.e., X), mediolateral (i.e., Y), and vertical (i.e., Z) axis displacement and velocity vectors were then resolved into two planar components – one acting along the projectile's principal trajectory (i.e., axial displacement and velocity), and a second acting normal to this trajectory (i.e., tangential displacement/velocity). Impacts were characterised by a rapid drop in axial velocity, during which the projectile decelerated from launching velocity to zero over a period of milliseconds (Fig. 4). We operationally defined the period of impact as beginning with the first frame in which axial velocity dropped below baseline launching speed, and ending when axial velocity reached zero. We then calculated several variables characterising the dynamics of the projectile's interaction with the target material during impact (Table 1).

We analysed a total of 37 high-speed video trials, including 19 trials with composite arrows (9 in clay and 10 in meat) and 18 trials with stone points (9 each in clay and meat). Given the relatively small sample sizes for each of the four experimental conditions, and the non-normality of several subsamples for particular experimental conditions, we used non-parametric aligned rank-transformed analyses of variance (ANOVAs) to analyse these data. In the case of significant interactions, Mann-Whitney U tests were used for post-hoc analyses of within cell differences (i.e., differences between responses to different material types within a given projectile type), adjusting p-values using the False Discovery Rate procedure [42]. All statistical procedures were implemented in the R statistical package (R Core Team, 2017), supplemented by the ARTool add-on package [41].

5. Results

5.1 Cutting

Each cutting test produced 400-500 data points for both load (N) and displacement (mm). There are clear differences in the loading levels required to cut the two materials with mean loads being roughly twice as great during the meat test relative to the clay, whereas maximum loads were nearly three times as great (Table 2). Mann-Whitney U tests confirmed that maximum and mean loading levels were significantly different between the two materials (p = .0001 in each instance). There are also differences between the two materials in terms of the variation observed in loading as the meat's coefficient of variation levels are more than double that of the clay (Table 2). Levene's test for homogeneity of variance returned significant results between each material for both mean and maximum values (p = .0001 and .0002, respectfully).

Figure 5 details typical load-displacement curves and material stiffness plots for each of the cut materials. As expected, the meat displays a J-shaped curve such that as the cutting edge starts to move towards the tissue (i.e. low displacement) it deforms under relatively low loads without fracturing. At larger displacement levels the meat stiffens and provides increasing resistance to the blades edge until such a point that any increased extension creates stress enough to permanently fracture the muscle fibres (i.e. a cut is formed). As detailed in Figure 5B, this process of load increases and then groups of muscle fibres fracturing repeats until the blade has passed through all of the muscle tissue. The stiffness plots for the meat follow the load-displacement curves and highlight both the 'bunching' nature of the muscle fibres and how stiffness increases when the meat is under relatively high deformation (Fig. 5D).

The clay displays a load-displacement curve that is highly consistent between samples (Fig. 5A) and similar to those returned by Wang and Gee-Clough [34]. There were no obvious points at which fractures were initiated in the material and the greatest stiffness was recorded for the first ~3 mm when the blade first entered the clay block. Stiffness also marginally increased towards the end of the cutting events when the greatest amount of the blade's surface area was in contact with the clay. Peak stiffness levels were substantially lower within the clay condition relative to the meat. Loading levels increase sharply at first and then more steadily until displacement reaches ~20 mm, before exhibiting a reverse trend of decreasing relatively sharply and then levelling out. Peak loading is consistently at the point prior to the blade's edge cutting through the bottom of the 20mm of clay. Consequently, it appears that the meat and clay display very different fracture mechanics, and that the clay displays very low elastic deformation prior to fracturing.

5.2 Projectiles

5.2.1 Penetration depth and speed

Descriptive statistics for the penetration depths and speeds of each projectile and material type are presented in Table 3. It is clear that both the composite arrows and stone points display differences in penetration depths when fired in the meat and clay, with the meat appearing to be more resistant (Fig. 6). Aligned rank-transformed ANOVA indicates the main effects for both projectile type and material type, and a significant projectile-by-material type interaction (Table 4). Specifically, the relative differences achieved by the stone points between the clay and meat is substantially lower than that observed for the arrows. Indeed, on average, arrows achieved penetration depths in clay that are roughly twice that of meat (Table 3; Fig. 6). As expected, given the systematic method for launching the projectiles, speed did not vary between the target material types, and there was no significant interaction between projectile type and material type. However, the lighter composite arrows were launched at significantly greater speeds than the relatively heavy stone points (Tables 3 and 4; Fig. 6).

5.2.2 High-speed video analyses of projectile impact dynamics

5.2.2.1 Validation

Summary statistics from the high-speed dataset are presented in Table 5. We used two methods to assess the validity of high-speed video based measures of projectile impact dynamics, relative to the other objective methods discussed above. First, we compared peak axial speed of the projectiles in our motion-tracking dataset to the launching speeds measured in the more extensive chronograph dataset. Peak axial speeds of composite arrows were slightly higher than the speeds in the chronographic dataset, with an average of 34.4 m/s (bootstrapped 95% CI: 33.7 - 35.1 m/s) (Table 5), whereas peak axial speeds for the stone points were slightly lower, with an average of 23.4 m/s (bootstrapped 95% CI: 22.5 - 24.3 m/s). Overall, the speeds measured by the two methods were similar, with some variation expected due to random variation among experimental days and measuring speeds at slightly different locations (i.e., chronograph speeds were measured immediately after launching, whereas motion-tracking data were taken closer to the impact with the target).

Second, we also assessed validity of our high-speed video dataset by directly comparing impact displacement estimated from motion-tracking to direct measurements of penetration depth from the projectile embedded in the target (note that direct measurements of penetration depth were only available for a subset of 23 trials). Although these two measurements are not expected to be identical, given that there could be residual movement and recoil of the projectile after the initial impact, the two measures should be close to one another. Overall, impact displacement and penetration depth were highly correlated (Fig. 7; Pearson's $r = .960$, $p < .001$). A least-squares linear regression fit indicated that measured depth scaled to estimated depth with a slope of 1.08 (95% CI: 0.936 - 1.22 and a y-intercept of -21.5 mm (95% CI: -44.5 – 1.59 mm). These scaling values are not significantly different from a line of identify (i.e., slope of 1.0 and intercept of 0) (Fig. 7). Moreover, residual deviations between estimated and measured penetration depths were not significantly positively nor negatively biased relative to zero (Fig. 7; binomial test: $p = .210$).

5.2.2.2 Impact Dynamics

The results of the two-way aligned rank-transformed ANOVAs of impact dynamics are summarised in Table 6. Variation in impact displacement was characterised by significant main effects for both projectile type and material type, and a significant projectile by material interaction (Table 6). Post-hoc tests revealed that for composite arrows, shots into a clay target were characterised by greater impact displacement than shots into meat targets. Stone points, by contrast, showed no significant variation in impact displacement between the two materials (Fig. 8a). Similar results were obtained in the larger penetration depth dataset discussed above, where we found that material-based differences in penetration depth were attenuated for stone points versus composite arrows. Variation in impact duration was characterised by a significant main effect for material type, and a significant projectile by material interaction, but not a significant main effect for projectile type alone. Post-hoc tests revealed that material type had opposite effects between the two projectile types, with clay targets being characterised by significantly longer impact durations for composite arrow shots, but meat targets being characterised by significantly longer impact durations for stone point shows (Fig. 8b). Work of impact did not vary between materials or show a significant projectile by material type interaction, only showing a significant main effect for projectile type, with shots by stone points being characterised by significantly greater work of impact than composite arrow shots (Fig 8c). Finally, variation in average impact force was characterised by a significant main effect for projectile type and a significant projectile by material interaction, though the main effect for material type was not significant. Post-hoc analyses showed that average impact force was significantly greater for meat targets for shots by composite arrows, whereas average impacts forces were similar across material types for shots by stone points (Fig. 8d).

6. Discussion and Conclusion

The use of industrially produced and/or synthetic materials as a substitute for 'meat' is common within a diverse range of disciplines. This includes the use of fresh clay, which has been suggested to be a suitable alternative to the use of meat during examinations of the ergonomic consequences of using different hand-held cutting tools [20]; [32]. Here we present a series of experiments that directly test whether clay is a reliable proxy for meat during cutting and projectile research.

Results indicate that when similarly sized portions of clay and meat are cut, the maximal and mean forces required to cut through meat are significantly greater than those required for clay. Indeed, mean force requirements for meat are roughly twice that of clay, while differences in maximum forces are three times as great. In short, meat provides greater resistance to a cutting edge than clay. Although we can only speak of the extent of this difference for beef, we believe it is reasonable to assume that other meats will display similar results. The greater difference recorded for the maximum force records appear to have been caused by both the presence of sinuous connective tissue in the meat and muscle fibres 'bunching up' to provide greater resistance to blade cutting edges. Certainly, although care was taken to avoid connective tissue in all meat portions, trials 19, 20, and 24 appeared near absent of this material and, in turn, retuned some of the lowest maximal force records. Inconsistencies in the material structure of meat also likely contributed to the greater coefficient of variation levels returned for this material, which are double that of clay.

Differences between the materials are highlighted by the load-displacement curves that detail how each material propagates fractures (i.e. cuts). Clay is characterised by very consistent curves between individual tests that are, at least partially, representative of the amount of surface area of blade wedged between the clay at a given time (i.e. the amount of blade surface area that could possible make contact with the clay, both at the blade's edge and sides). Certainly, it is clear that as the blade starts to exit the clay and no more material is being cut, force reduces in a consistent manner. Further, the greatest force is recorded at a blade displacement of 20 mm, when the entirety of the blade's surface area is within the clay (Fig. 5). In other words, some of the resistance provided by the clay appears to be caused by friction acting against the surface of the blade. It is, however, clear that the first ~2.5 mm of displacement (i.e. when the blade's tip enters the clay) displays a notable increase in force relative to displacement (Fig. 5). This is consistent between individual clay tests. The clay was fresh in all instances, so we do not think this trend can be attributed to a 'skin' forming on the outside of the material samples. Blade tip geometry appears to be the cause of this phenomenon as the wedged aspect was 2 mm deep, meaning that resistance progressively increased for the first 2 mm of displacement. As highlighted by Wang and Gee-Clough [34] there was likely a combination of wedge and sheer distortion dependent on the micromorphology of the blades tip, however, in contrast to their study and in line with Stafford [43], fracture propagation is likely to be best described as a flow pattern and not material failure.

Conversely, meat displays a J-shaped curve where it initially easily deforms without fracturing, but goes on to stiffen, provide increases resistance to the cutting edge, and then finally fractures when extension and loading creates enough stress in the material. In this way meat builds up tension and resistance to fracture as muscle fibres 'bunch-up' before fracturing, in turn leading to the characteristic 'jagged' load-displacement curve as the blade cuts through the meat (Figure 5). In contrast, the clay displays no obvious points at which fractures occur. Further, meat undergoes elastic deformation prior to fractures initiating, such that edge loading does not, at least at the very start of cutting processes, create irreversible damage to the material's surface. Clay, however, at first displays minimal plastic deformation before parting and forming material separation. It is unclear whether at a microscopic level clay displays elastic deformation. It is important to highlight that the addition of variation in rake angle, direction of cutting, included (edge) angle, cutting edge size and surface area, and slice-push ratio may alter the strength of relationship observed here, but are unlikely to change the overall distinction in material performance.

Meat and clay do, therefore, display clear differences in their fundamental cutting mechanics. This is not particularly surprising and, in turn, clay would not make a suitable alternative to meat during tests of cutting edge fracture mechanics during meat processing behaviours. The results presented here also clearly detail that there are significant differences in the resistance provided to cutting edges between these two materials. However, experiments concerned with the consequences of meat cutting, such muscle fatigue during tool use or torque experienced by a hand-held tool, may reasonably use clay as a replacement for meat, so long as they are aware of the differences in required forces. McGorry [20]; [32] was, therefore, justified in his use of clay as a substitute for meat when examining gripping forces and upper limb kinematics during knife use, although the present results suggest that the forces recorded in these experiments may be less than those experienced in 'real-world' butchery events. Future experiments may profitably examine whether other meats, such as poultry, return similar results to those provided here, and how different types of clay (e.g. modelling or kaolin) compare to the potters' clay used here.

The projectile tests returned similar results to the cutting tests insofar as meat provided greater resistance to penetration than clay. It is notable, however, that relative differences between the two materials for the stone points is substantially lower than it is for the composite arrows. That is, in terms of depth of penetration, clay appears a closer proxy for meat for stone points than for the composite arrows. These results are corroborated by the high-speed video analyses of each projectile's impact dynamics when fired into the two materials: clay provided significantly greater impact displacement than the meat for the composite arrows, but no significant difference for the stone points. Therefore, even though the work of impact is similar (because the loss of kinetic energy is similar, given that the arrows were travelling at set speeds), the average force required to stop the arrow is greater for shots into meat. The differences in the comparability of clay and meat, dependent on the projectile, is likely due to the form and mass of each projectile. That is, despite the stone point displaying greater work of impact, its greater surface area meant that its energy dissipated in totality at earlier depths of penetration. In turn, there was reduced potential for any disparities between meat and clay to accrue into significant differences. In sum, the high-speed video analyses and depth of penetration tests suggest that, dynamically, clay can be used as a suitable substitute for meat during experimental archaeology tests with stone points, but not for modern composite arrows. That is, for studies concerned with the performance of reasonably large projectile tips (such as those often observed in the Palaeolithic archaeological record), clay may be used as reliable proxy for meat. In sum, when both sets of tests are combined, it appears that clay has the potential to be of use within cutting and projectile experiments, however, caution should be used when assessing its suitability as a reliable proxy for meat.

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Figures

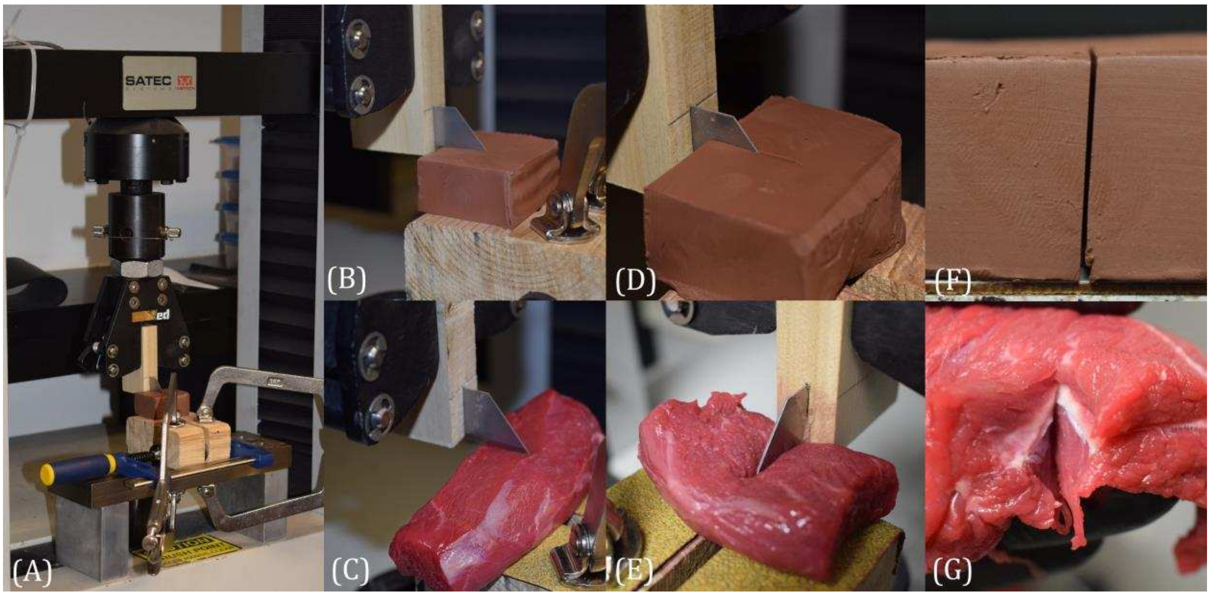

Figure 1: Images identifying the Instron® tensile testing machine and experimental set-up when cutting the clay and meat. Images B and C depict blade placement at the start of each cutting test, D and E depict material deformation prior to fracture for the meat (E) and the lack therefore for the clay (D). Images F and G show segments of each material after they have been cut. In clay (F), it is clear that no deformation prior to fracture occurs when the cut is initiated, however, there is potential for marginal material tearing as the blade edge exits. The meat segment (G) was not included in the data sample but highlights the potential for connective tissues to alter the resistance provided by 'meat' relative to muscle fibres.

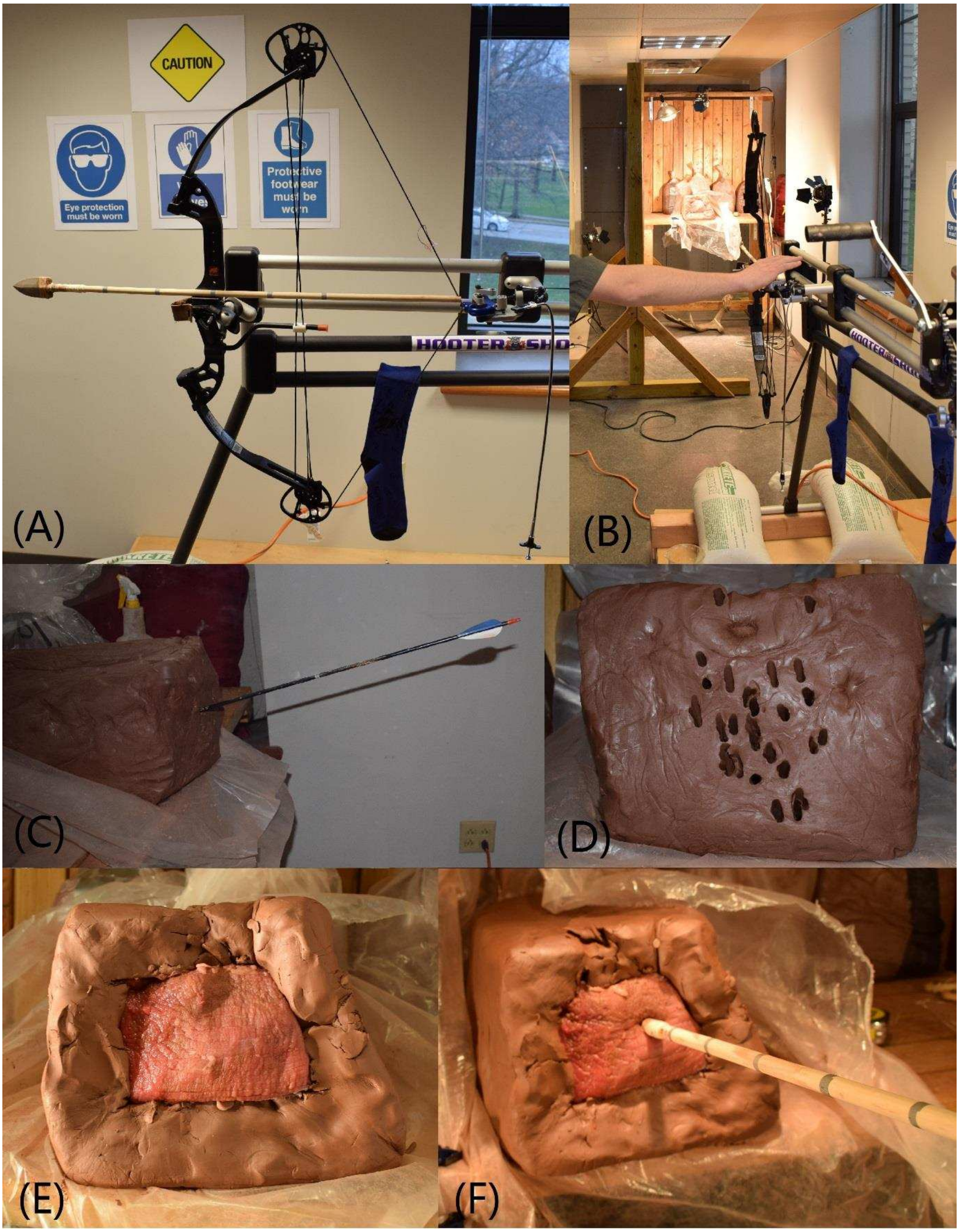

Figure 2: Images identifying the composite bow (A) and projectile range (B) used during this experiment. The clay (C and D) and meat (E and F) targets are also detailed, as are an arrow (C) and stone point (F) after having been fired at the target. Note the reflective tape markers spaced along the length of the projectiles' shafts.

Figure 3: The composite arrow and stone point projectiles used in the penetration experiments. The scale bar is 10cm long in all instances.

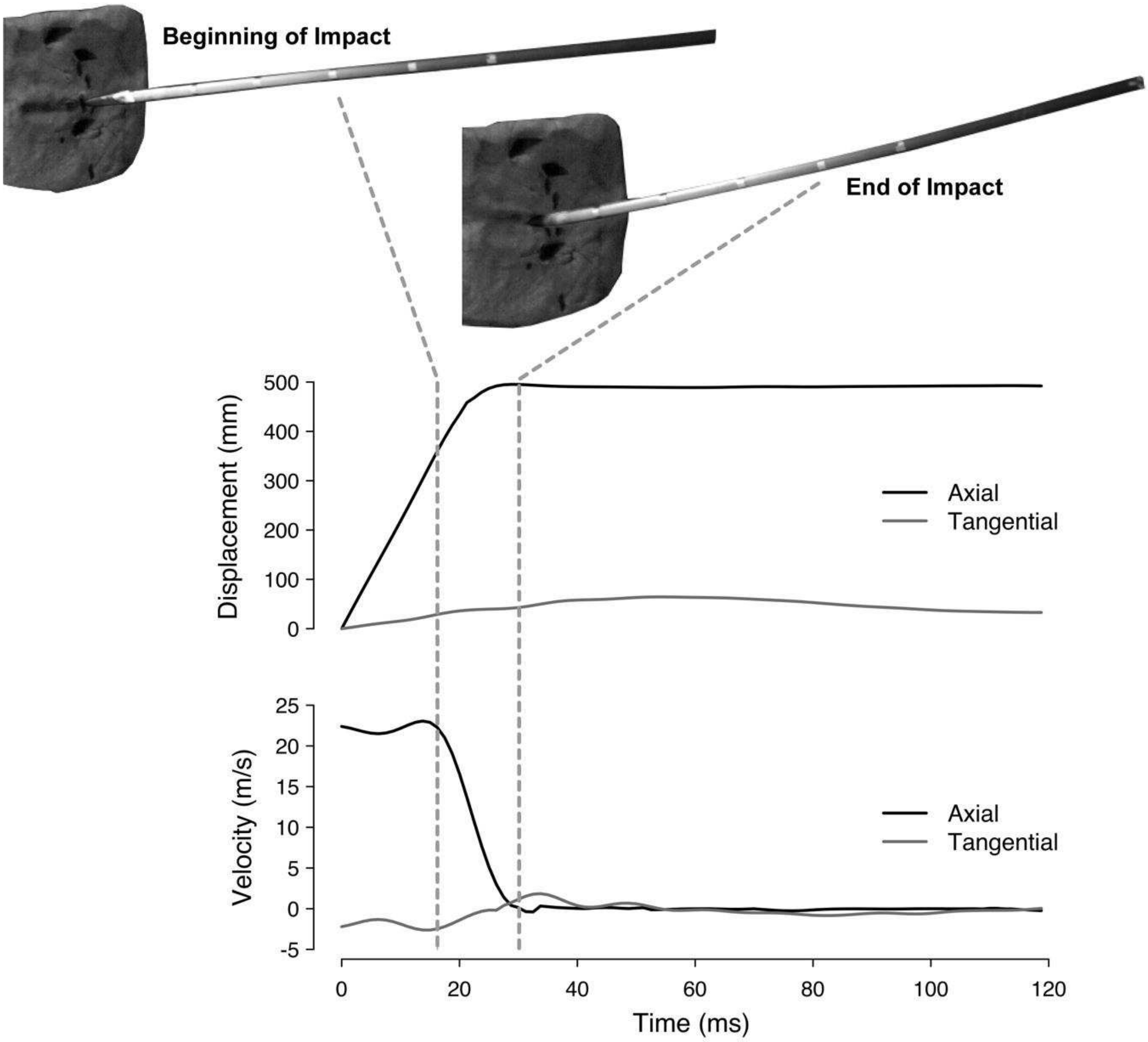

Figure 4: Kinematics of a projectile impact. An exemplar trial of the stone point impacting the clay target is illustrated, with graphs showing instantaneous changes in axial and tangential displacement and velocity during the period of impact. The images at the top were rendered from the high-speed video and digitally enhanced and cropped to better illustrate impact events ('mm' = millimetres, 'm/s' = meters per second, 'ms' – milliseconds).

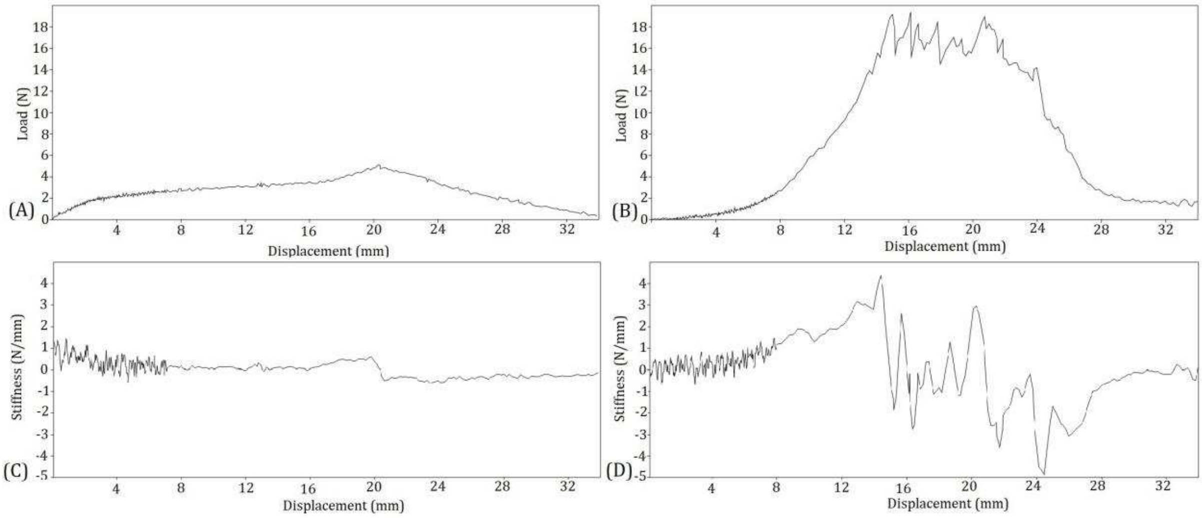

Figure 5: Load-displacement curves during the clay (A) and meat (B) cutting tests ('N' = newtons). The corresponding stiffness-displacement curves for clay (C) and meat (D) are also depicted.

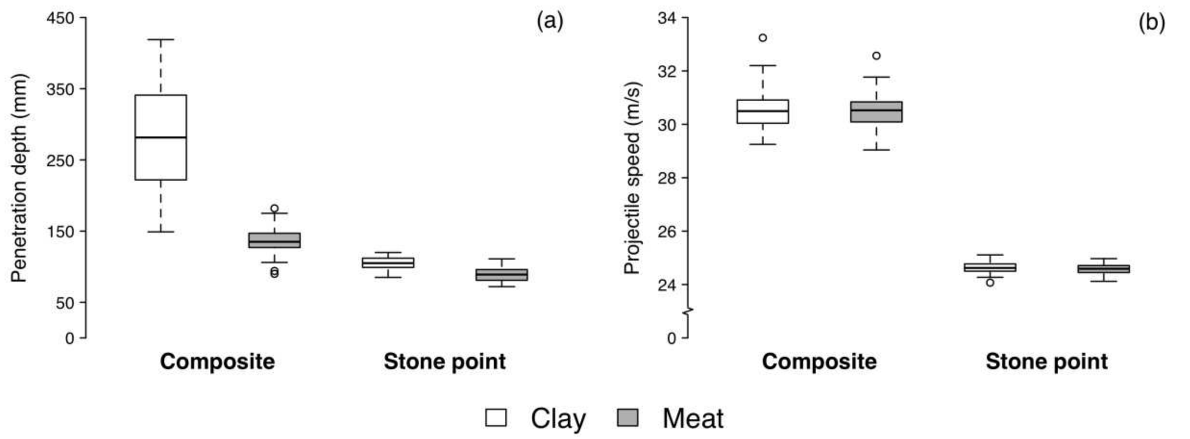

Figure 6: Box-and-whisker plots of variation in projectile penetration depths and speed, as a function of projectile and material type during the high-speed camera tests ('mm' = millimetres, 'm/s' = meters per second). In each plot, bold lines indicate the median of the distribution, boxes extend to the 1st and 3rd quartiles, and whiskers extend to the most extreme data points that are no more than ±150% of the interquartile range. Outliers beyond this range are indicated by individual symbols.

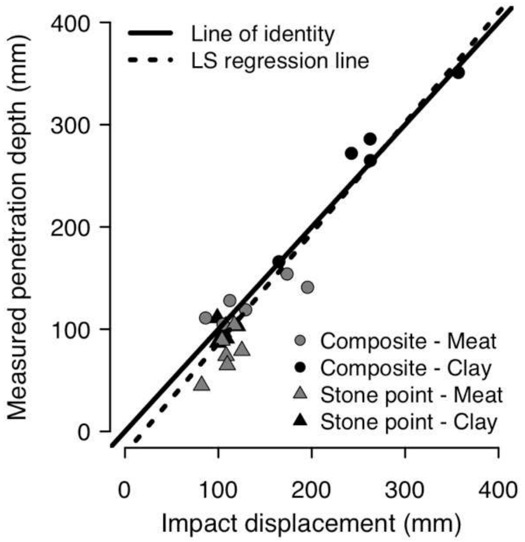

Figure 7: Validation of motion-tracking analyses of projectile dynamics. Measured penetration depths are plotted against axial projectile displacement during the period of impact ('mm' = millimetres).

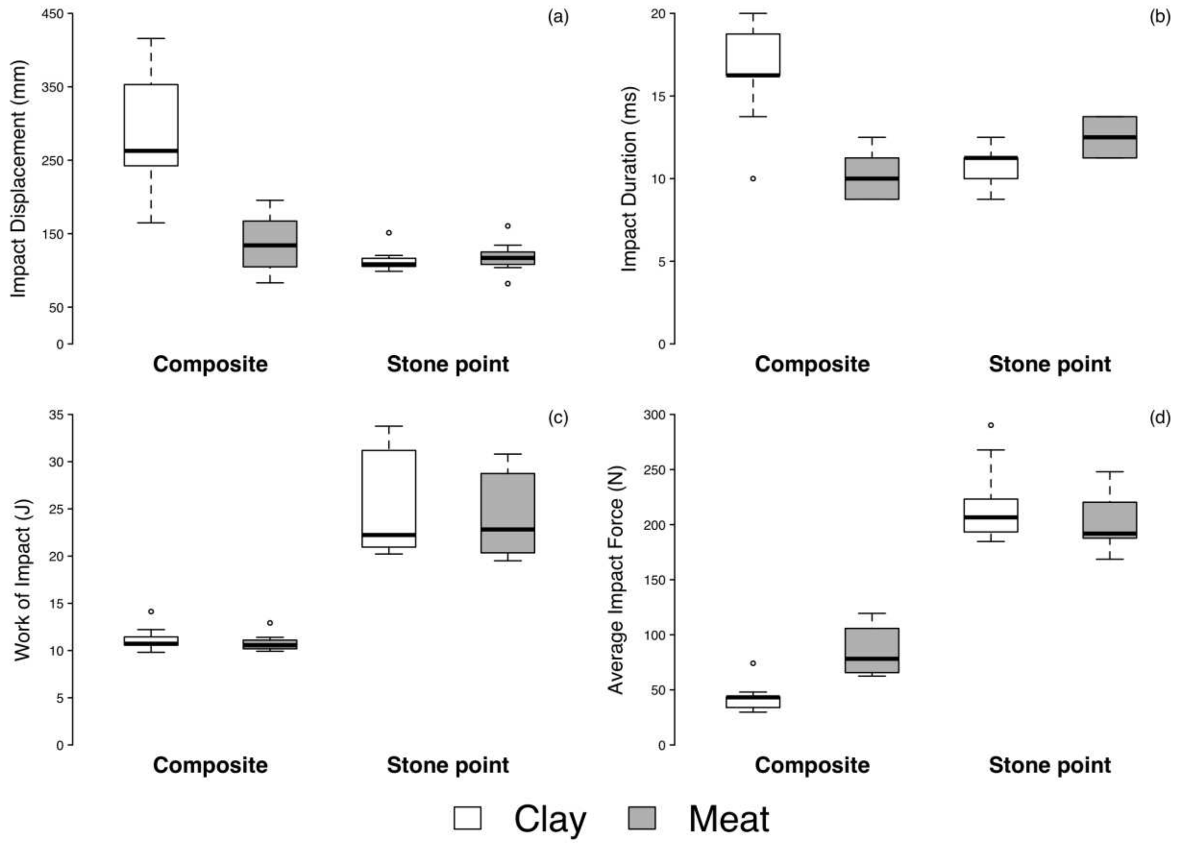

Figure 8: Box-and-whisker plots of variation in projectile impact dynamics, as a function of projectile and material type (‘mm’ = millimetres, ‘ms’ = milliseconds, ‘J’ = joules, ‘N’ = newtons). In each plot, bold lines indicate the median of the distribution, boxes extend to the 1st and 3rd quartiles, and whiskers extend to the most extreme data points that are no more than ±150% of the interquartile range. Outliers beyond this range are indicated by individual symbols.

Tables

Table 1: Summary high-speed video measurements of projectile impact dynamics.

Variable	Definition
Impact displacement	Axial distance in centimetres (cm) traversed by the projectile during the period of impact.
Impact duration	Time in milliseconds (ms) between the start of projectile deceleration and the cessation of motion.
Work of impact	Work in Joules (J) performed by the target in stopping the projectile – or, equivalently, work performed by the projectile in penetrating the target. Equal to the change in the kinetic energy of the projectile during the duration of impact, where kinetic energy was calculated as one-half the product of projectile mass and the square of instantaneous projectile velocity.
Average force of impact	Average force in Newtons (N) required to arrest projectile motion – equivalent to "stopping power". Calculated as work of impact divided by impact displacement.

Table 2: Descriptive loading data for the two raw materials analysed during the cutting tests (n = 30 in all instances). 'Mean Load' refers to the average load recorded across a single cutting test ('N' = newtons, 'S.D.' = standard deviation, 'C.V.' = coefficient of variation).

Trial	Clay		Meat	
	Max. Load (N)	Mean Load (N)	Max. Load (N)	Mean Load (N)
Mean	5.2	2.6	16.3	5.8
Minimum	4.1	2.0	8.7	2.2
Maximum	7.1	3.3	25.9	11.8
S.D.	0.7	0.3	4.5	1.7
C.V.	13.3	12.0	27.9	29.8

Table 3: Descriptive data detailing the primary penetration depth and speed data of the composite arrows and stone points when fired into clay and meat ('mm' = millimetres, 'm/s' = meters per second, 'S.D.' = standard deviation, 'C.V.' = coefficient of variation).

		Composite Arrows (n = 204)		Stone Points (n = 60)	
		Meat (n=102)	Clay (n=102)	Meat (n=30)	Clay (n=30)
Penetration (mm)	Mean	137.3	281.4	88.8	104.8
	S.D.	17.2	73.6	10.2	8.8
	C.V.	12.6	26.2	11.5	8.4
Speed (m/s)	Mean	30.5	30.5	24.6	24.6
	S.D.	0.6	0.6	0.2	0.2
	C.V.	2.1	2.1	0.8	0.9

Table 4: Aligned rank-transformed analyses of variance of the penetration depths, speed and projectile dynamics of the composite arrows and stone points when fired into clay and meat (‘mm’ = millimetres, ‘m/s’ = meters per second, ‘J’ = joules, ‘N’ = newtons).

		Projectile	Material	Interaction	Post-hoc tests
Penetration depth (mm)	F-value	284.6	381.0	100.4	Composite: U = 10301.5, p < 0.001 Stone point: U = 790.5, p < 0.001
	Degrees of freedom	1, 260	1, 260	1, 260	
	p-value	< 0.001	< 0.001	< 0.001	
Speed (m/s)	F-value	289.6	0.04	0.08	NA
	Degrees of freedom	1, 260	1, 260	1, 260	
	p-value	< 0.001	0.846	0.778	
Impact Displacement (mm)	F-value	42.5	30.9	33.0	Composite: U = 87, p < 0.001 Stone point: U = 30, p = 0.39
	Degrees of freedom	1, 33	1, 33	1, 33	
	p-value	< 0.001	< 0.001	< 0.001	
Impact Duration (ms)	F-value	3.5	24.3	44.6	Composite: U = 85.5, p = 0.002 Stone point: U = 16, p = 0.027
	Degrees of freedom	1, 33	1, 33	1, 33	
	p-value	0.07	< 0.001	< 0.001	
Work of Impact (J)	F-value	99.6	0.9	0.2	N/A
	Degrees of freedom	1, 33	1, 33	1, 33	
	p-value	< 0.001	0.348	0.673	
Average Impact Force (N)	F-value	99.7	20.3	17.2	Composite: U = 5, p = 0.003 Stone point: U = 52, p = 0.331

Table 5: High-speed video analyses of projectile impact dynamics (‘mm’ = millimetres, ‘m/s’ = meters per second, ‘ms’ = milliseconds, ‘J’ = joules, ‘N’ = newtons, ‘S.D.’ = standard deviation, ‘C.V.’ = coefficient of variation).

		Composite Arrows (n = 19)		Stone Points (n = 18)	
		Meat (n=10)	Clay (n=9)	Meat (n=9)	Clay (n=9)
Peak Axial Speed (m/s)	Mean	34.0	34.8	23.2	23.5
	S.D.	1.24	1.85	1.67	2.39
	C.V.	3.65	5.32	7.20	10.20
Impact Displacement (mm)	Mean	135.4	280.8	118.2	113.3
	S.D.	38.74	79.83	21.83	15.92
	C.V.	28.61	28.43	18.47	14.05
Impact Duration (ms)	Mean	10.0	16.2	12.4	10.8
	S.D.	1.32	3.00	1.16	1.25
	C.V.	13.20	18.50	9.35	11.60
Work of Impact (J)	Mean	10.8	11.2	24.0	24.9
	S.D.	0.90	1.33	4.54	5.71
	C.V.	8.33	11.90	18.90	22.90
Average Impact Force (N)	Mean	85.1	42.7	204.0	220.0
	S.D.	22.6	13.4	25.4	36.1
	C.V.	26.6	31.4	12.5	16.4