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COMPARISON OF MAXIMUM FORCES REQUIRED TO PENETRATE TEN AND TWENTY PERCENT BALLISTICS GELATIN, MEAT, AND CLAY TO ASSESS VARIATION BETWEEN TARGET MEDIA IN ARROW PENETRATION STUDIES (60 pp.)

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For hundreds of thousands of years, *Homo sapiens* and our hominid ancestors have used projectile weapons made from various materials to hunt prey. Two key variables that determine hunting success are the level of penetration depth achieved by the weapon tip and the injury caused due to the shape, or cross-section, of the points as they tear through a target's body. To better understand ancient weapon systems, experimental archaeologists have been putting various projectile point technologies to the test using several differing ballistics setups and target materials. However, the lack of consistency in target materials used for ballistics testing is highly problematic. At a minimum, the results are inconsistent across tests and can result in unequivocal datasets.

Understanding how projectiles penetrate a given target material is key to determining projectile point efficiency and assessing wound damage. This study evaluates stone and steel points against four target materials: clay, ten and twenty percent ballistics gelatin, and meat, to assess the amount of force required to penetrate each material to a controlled depth using an Instron

Materials Tester. The goal was to develop a baseline understanding of how the materials react during the penetration process for ongoing and future studies that will be conducted at the Kent State University Experimental Archaeology Laboratory and elsewhere.

The results of this study show that for internally valid tests that wish to achieve consistent results within the mean maximum resistance force of meat during static testing, then calibrated twenty percent ballistics gelatin is the best material to use. However, given the cost of purchasing twenty percent ballistics gel and the difficulty of making it oneself, I conclude that if the experiment seeks to mimic the range of variation found in meat in static testing, while still yielding results within the lower bounds of the mean maximum resistance force, then commercial clay is the most similar material to the variation found within meat while also being the most logistically simple to work with and also offers cost-effectiveness.

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IN ARROW PENETRATION STUDIES

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Chapter 1: Introduction

For hundreds of thousands of years, *Homo sapiens* and our hominid ancestors have used projectile weapons made from various materials including stone, bone, wood, and eventually metal to hunt prey. Archaeological evidence shows that complex, compound, technologies like the bow and arrow have been used as long as humans have practiced agriculture; some 10,000 years or more (Baker, 1994), with newer finds suggesting they may stretch back even further, as much as 64,000 years ago (Lombard & Phillipson, 2009). Indeed evidence of simple, hurled weapons dates back to over 40,000 years ago in Europe (Sano et al., 2019) and 270,000 years ago in Africa (Sahle et al., 2013). Successful hunting weapons were a key advantage that led to our evolutionary success as a species, and thus, figuring out how various projectiles functioned, and then evolved, can shed much light on the past human behavioral adaptations. Given that a successful kill was essential for human survival and ultimately led to our spread around the globe, archaeologists often focus on understanding the variation in projectile weapon tips, and how this variation may have affected overall hunting success.

Two key variables that determine hunting success are the level of penetration depth achieved by the weapon tip and the injury caused due to the shape, or cross-section, of the points as they tear through a target's body (Kruse, 2010; Wood & Fitzhugh, 2018b). Deeper penetration yields a larger cavity in the body of the target allowing the loss of more blood loss and likely causing more damage to the portion of the body hit, including an increased likelihood of damaging vital organs in the thoracic region; The best results coming from the projectile passing fully through the target (Karger et al., 1998; Peloponissios et al., 2001). Meanwhile, asymmetrically shaped lacerations created by specific point shapes result in a wound that is incised and less likely to close, thus increasing the loss of blood through the gash created by the penetrating object and keeping the projectile body from blocking blood loss (Karger et al., 1998; Wood & Fitzhugh, 2018b). Both of these factors are important and contribute to a cleaner, more rapid kill (Karger et al., 1998; Wood & Fitzhugh, 2018b). Experimental studies to understand how past technology has impacted these two factors have been ongoing in archaeology (Karger et al., 1998; Mullen et al., 2021; Shergold & Fleck, 2005; Sitton et al., 2020; Wood & Fitzhugh, 2018b), however when assessing either of these variables in a lab setting, the target material is of key concern.

To better understand ancient weapon systems, experimental archaeologists have been putting various projectile point technologies to the test using several differing ballistics setups and target materials. These target material include carcasses (Karger et al., 1998; Devin B. Pettigrew et al., 2015; Devin Brent Pettigrew, 2015; Wood & Fitzhugh, 2018b), various cuts of meat (Philip S. L. Anderson & LaBarbera, 2008; Goldstein & Shaffer, 2017; Pargeter et al., 2016; Sisk & Shea, 2009), archery targets (Wilson et al. 2021; Whittaker 2013, 2014; Sisk and Shea 2009), ballistics gelatin and similar media (Philip S. L. Anderson et al., 2016; Philip S. L. Anderson & LaBarbera, 2008; Karger et al., 1998; Kruse, 2010; Milks et al., 2016; Scott et al., n.d.; Waguespack et al., 2009; Wilkins et al., 2014; Wood & Fitzhugh, 2018b), and others, such as clay and cantaloupe (Mika et al., 2020; Devin B. Pettigrew et al., 2015). In general, lab-based scientists prefer a target material that is ethical, affordable, and sanitary. Indeed, Kent State University's Experimental Archaeology Laboratory, along with a few other labs around the world, have conducted numerous ballistics studies using processed clay as a target medium to test the performance of various projectiles (Michelle R. Bebber & Eren, 2018; Lowe et al., 2019; Mika et al., 2020; Mullen et al., 2021; Wilson et al., 2021) based on the results of Key et al., (2018), which demonstrated the efficacy of clay as a proxy for meat when using stone projectile tips.

1.1 Problem:

The lack of consistency in target materials used for ballistics testing is highly problematic. At a minimum, the results are inconsistent across tests and can result in equivocal datasets. Understanding how projectiles penetrate a given target material is key to determining projectile point efficiency and assessing wound damage. The goal of this study is to begin establishing parameters for the accurate testing of ballistics technologies, both past and present, based on previous experiments conducted by Karger et al., (1998) and Key et al., (2018). It is an essential first step in a series of tests that aim to ensure standardization in penetration studies, and it will provide the data necessary for understanding a key component central to the testing projectile efficiency. To address the issues discussed above, we conducted a series of controlled tests using principles of material science and experimental archaeology.

1.2 Why Experimental Archaeology?

David Clark defined archaeology as the study of data clustered into archaeological entities based on socio-political groups of the past; often described as cultures and defined in their temporal context through the use of archaeological data and models (Clarke, 1978). We generate these models through the isolation of essential factors and interrelationships to help simplify, partially represent, and predict, complex human behavior (Clarke, 1972). Models to conceptualize the processes that generate innovation, stimulate its acceptance, and lead to its dissemination to other entities are of crucial importance to archeology as they help us understand how ideas, knowledge, and technology are transported through space and time (Stockhammer & Maran, 2017). I define culture in this context as: "information that is acquired from other individuals via social transmission mechanisms such as imitation, teaching, or language. (Mesoudi, 2011)" Thus, understanding how and why individuals in the past made the technological decisions they made are imperative to archaeology. Without models to describe the selection processes of our ancestors, we cannot understand how culture developed and evolved during our past.

1.3 Target Materials used in Ballistics Testing

Undoubtedly, there are many considerations to make when choosing target materials for archaeological experiments. Factors like funding, logistics, ethics, cleanliness, internal validity (i.e. controlled experiments) or external validity (i.e. replicative experiments) (Eren et al., 2016; Iovita & Sano, 2016), and, most importantly, the question being asked, all weigh heavily upon the choice of target medium used for a given test. However, the assumption that some materials perform better than others is misleading and highly dependent upon the study and question being asked by the researcher. For example, most modern ballistics tests of firearms conducted in the United States are performed on 10% FBI calibrated ballistics gelatin as a target material because studies show it to be a reasonable substitute for muscle tissue due to its elastic deformation (Carr et al., 2018; Coupland et al., 2011; Fackler & Malinowski, 1985; Fuliful et al., 2017; Jin et al., 2018; Krauss & Miller, 1960; Mabbott et al., 2016; Subhash et al., 2012). Yet, in Europe and other parts of the world ballistics tests of firearms are instead performed on glycerin soap, which deforms plastically, and thus, better mimics flesh and fat while retaining wound cavities that represent the energy delivered by the projectile as it passes through it (Coupland et al., 2011;

Mabbott, 2015; Schyma, 2020). Furthermore, concentrations of ballistics gel vary by testing organization, with the FBI preferring 10% concentration by mass of gelatin while NATO prefers 20% concentrations (Carr et al., 2018; Fackler & Malinowski, 1985; Jin et al., 2018; Mabbott, 2015; Maiden et al., 2015; Mattijssen et al., 2016; Schyma, 2020) and standards on manufacture, storage, and calibration, which are required in firearms studies (Carr et al., 2018; Coupland et al., 2011; Fackler & Malinowski, 1985; Mabbott, 2015; Mabbott et al., 2016; Maiden et al., 2015; Schyma, 2020), are rarely mentioned in archaeological reports.

1.3.1 Ballistics Gelatin

Ballistics gelatin, sometimes referred to as ballistics ordnance gel, ballistics gel, gelatin, etc., is a translucent material made from acid-treated collagen and water (Carr et al., 2018; Subhash et al., 2012). It has been used by researchers who seek to visually assess the wounding characteristics of projectiles for decades as a simulant for flesh (Jussila, 2004). Most modern ballistics tests that use gel create and calibrate it to standards outlined in Fackler & Malinowski, (1985, 1988), which specify a 10% gelatin to warm water ratio slowly heated to 40 degrees Celsius and calibration using a 4.5mm steel pellet fired at 180m/s and penetrating the block 85 +/- 5 mm. The blocks should be cooled at 7 – 10 degrees Celsius overnight and tightly wrapped and stored at 4 degrees Celsius. Multiple groups have suggested modifications to this recipe and include inclusions of other types of microbial growth inhibitors, distilled water, hot water, various cooling and storing strategies. Opinions differ on whether or not excessive heat during manufacture affects the final product (Carr et al., 2018; Jussila, 2004; Maiden et al., 2015; Mattijssen et al., 2016). More recent studies, including those by Jussila, (2004); Maiden et al., (2015); Mattijssen et al., (2016) seek to further regulate and standardize methods of production and storage of gelatin and have been adopted by many (Carr et al., 2018). Regardless of methodology, all agree that whatever process is used should meet the standard of a bloom score of 250 – 300 (a number derived from the pellet test above) at the time of testing to yield relevant results, and methods of manufacture and storage should be documented by the researchers (Carr et al., 2018; Fackler, 1990; Fackler & Malinowski, 1985, 1988; Jussila, 2004; Maiden et al., 2015; Mattijssen et al., 2016; Schyma, 2020; Subhash et al., 2012). However, some studies (e.g., Waguespack et al. 2009) that used ballistics gelatin failed to outline the processes of manufacture, calibration methods, or storage procedures used, which can be problematic.

Other concerns about ballistics gelatin center around the type used. Paraffin-based gels like Perma-Gel and Clear Ballistics, which are reusable, clearer, and easier to handle than water-based gelatin, have been shown to yield different penetration results when compared to their FBI and NATO counterparts, despite having the same concentrations of gelatin (Appleby-Thomas et al., 2016; Courtney et al., 2017; Mabbott, 2015; Mabbott et al., 2013). However, it should be noted that one of the tests making this claim, Courtney et al., (2017) used small sample sizes that were taken from a website showing studies performed by a bullet manufacturing company into Clear Ballistics Gel. They then compared the videos to their study of the same ammunition in standard 10% FBI calibrated gelatin. For their part, Clear Ballistics asserts that its products are calibrated using the standards set forth in (Fackler & Malinowski, 1988) and meet FBI and NATO protocols for testing (*Clear Ballistics*, 2021).

1.3.2 Living Organisms or Cadavers

For many researchers, using a material like ballistics gelatin, regardless of its benefits, is simply cost-prohibitive and, while many agree that it is a good simulant for tests using firearms and bullets, they also note that its best use is illuminating the expansive forces and cavitation properties of bullets as they pass through simulated flesh (Appleby-Thomas et al., 2016; Carr et al., 2018; Coupland et al., 2011; Fuliful et al., 2017; Krauss & Miller, 1960; Mabbott, 2015; Mabbott et al., 2013; Maiden et al., 2015; Schyma, 2020; Stevenson et al., 2020). However, in most archaeological studies, particularly those focusing on studies of projectile weapons, this becomes irrelevant. Pointed projectiles like arrow tips have drastically different penetration mechanics because of their shape, among other things. Their ability to form and propagate cracks (cut) in target materials, as well as how they travel through a target, fall under entirely different puncture mechanics than bullets, which push into targets more than slice (Atkins, 2009). Studies that have tested the efficacy of ballistics gel as a target medium for projectile points have determined that it is not an accurate analog for biological tissue (Coupland et al., 2011; Karger et al., 1998, 2004). The experiments conducted by Karger et al. were particularly important to understanding how arrows perform in ballistics gelatin and should be considered further.

Karger et al. (1998) focused upon the effects of arrow injuries in soft tissues and compared the results of penetration wounds across three media: recently deceased pig carcasses, glycerin soap, and ballistics gelatin. The stated purpose of the study was to understand the differences in the way different arrow types; a brass field tip, an iron triangular tip, an iron chisel-shaped tip, a German bodkin, and a needle bodkin, some shot using different weapons; a longbow, a crossbow, and a compound bow; performed within the different target media as they penetrated them. They found that not only did the arrows show significant differences in the penetration depths among the three target media, but that the variation across the different tip types was inconsistent. Specifically, they found that “the field tips penetrated deeper in gelatin than in nonbone tissue but broadheads showed the opposite behavior” (Karger et al., 1998). Eventually concluding that “the penetration depth in gelatin and especially in soap does not come even close to that in non-bone tissues, both media are unsuitable for experimental simulation of arrow wounds" (Karger et al., 1998). Thus, not only did both glycerin soap and ballistics gel yield different results than should be expected but the results were highly dependent upon the shape and style of arrowhead used (Karger et al., 1998). Their conclusion about using glycerin soap was echoed by Coupland et al. (2011; 150), who felt that "Soap is unsuitable for experiments involving projectiles that have low impact velocities (arrows, crossbow bolts, etc.) or jets of gas or fluid (alarm pistols, rocket motors, etc.) Such "projectiles" penetrate significantly less, if at all".

The claim that ballistics gel is the best material for studying wounding properties is a broad generalization. While its ability to simulate flesh when studying the wound tract, cavitation properties, and depth of penetration of bullets is acknowledged and agreed upon by many (see above), it is accepted as such based upon the caveat that the most accurate and externally valid (Eren et al., 2016) or replicative (Iovita & Sano, 2016) target medium is a live human body, or a proxy thereof (Coupland et al., 2011; Karger et al., 1998; Maiden et al., 2015). While the ethics involved with testing a live human need not be discussed here, it is often thought that using live or recently deceased animals, usually hunted wild game or farm-raised, is the next best substitute (Carr et al., 2018; Coupland et al., 2011; Karger et al., 1998; Maiden et al., 2015; Stevenson et al., 2020). However, using live animals raises ethical concerns while the dynamic nature of using a moving target hinders efforts to assert controls on an experiment. Using cadavers can also create ethical concerns and still places limitations upon the elements that the researcher can control (Karger et al., 1998). And while the logistics of finding, successfully hitting, and killing a live animal are obvious, there are also challenges when using cadavers, the most important being temporal (Jin et al., 2018; Karger et al., 1998). As non-living cadavers, all animal carcasses begin to decompose from the moment of death. Therefore, the level of decay, the temperature of the body, and time constraints upon studying the results before decomposition affect the tests are all important considerations to make when designing experiments. Other issues that arise from the inclusion of bones and organs within living or cadaverous targets, which may enhance the external validity and replicative value of the experiment, but can create concerns when attempting to determine wounding and penetration capabilities (Karger et al., 1998). Ultimately, the decision to use animals, whether live or cadaver positions increased control against external validity, along with considerable ethical and logistical issues.

1.3.3 Butchered Meat

As a means of avoiding some of the issues involved with live specimens or cadavers, while maintaining a higher level of external validity, some studies use store-bought or butchered meat (Philip S. L. Anderson & LaBarbera, 2008; Goldstein & Shaffer, 2017; Key et al., 2018; McGorry, 2001; Pargeter et al., 2016; Sisk & Shea, 2009). However, like cadavers, meat is tenderized as time passes from the moment the animal dies, due to “the breakdown of the muscle fibers by enzymatic action during proteolysis” (Leygonie et al., 2012, p. 96). As decomposition continues, the tissue itself begins to change at a cellular level and many of the fibers begin to lose their elasticity and rigidity, resulting in an increasingly softer matrix. To stall the decomposition process in meat, it can be frozen. However, the process of freezing itself causes changes in the structures of the tissue at the cellular level. These changes in cellular structure, reduce the shear force, measured in peak force, required to cut meat. (Lagerstedt et al., 2008; Leygonie et al., 2012). This then leaves the researcher with two options, both with diminished ability to mimic live flesh. A strict regimen of cooling meat and then using it quickly can help ease the decomposition issue but introduces new challenges in logistics as using the meat promptly and then returning it to a cooled state or otherwise reducing the amount of time it is allowed at room temperature can be problematic. This process also then exposes the question as to what temperature should meat be used, as its resistance and elasticity vary at different temperatures. Meat also lacks skin, which means that it does not fully imitate flesh. While some tests have simulated skin by adding a layer of animal hide over ballistics gelatin (Waguespack et al., 2009), the added effects of skin resistance were not a consideration in this experiment, which focused on the material properties of each target medium alone. Likewise, the grain of the fibers and underlying fats or sinew can affect the consistency of resistance in the medium (Key et al., 2018), which should be accounted for during the selection of the targets. Finally, it should be noted that the compressive forces that are exerted upon muscles when in a living or deceased body are lost when the meat is cut and processed. This means that the researcher must put some kind of compressive force upon the meat to hold or support it while testing (see: Key et al. 2018). In essence, while butchered meat is a suitable substitute for penetration studies using hafted points it ultimately cannot fully simulate the musculature, skin, bones, organs, and tensile forces at play in a live specimen; nothing short of a living specimen can. Therefore, while the use of store-bought, butchered meat is more accurate to a real-world scenario, it may not be ideal for studies that require strong external validity.

1.3.4 Commercial Pottery Clay

To avoid the costs involved with ballistics gelatin and the complications of using cadavers and meat, some have turned to commercial potter's clay as a target medium (Michelle R. Bebber & Eren, 2018; McGorry, 2001; Mika et al., 2020; Mullen et al., 2021). Potter's clay displays similar qualities to glycerin soap, being plastically expansive and retaining its shape after penetration (Coupland et al., 2011; Schyma, 2020), and some scholars (Schyma 2020) imply that they share many characteristics as target media. However, Coupland et al. (2011)

consider clay to be a poor target material, unless studying cavities, arguing that experiments using it are hard to replicate and inconsistent in their results, which are only useful for relative studies (Coupland et al., 2011, p. 177). An argument can also be made that, though they did not directly study clay as a medium, the conclusion reached by Karger et.al (1998) indicating that glycerin soap is a poor material for testing projectiles points may imply that clay would be as well, as Schyma et al. (2020) suggest that both media show similar characteristics. However, a study done by Key et al. (2018) set out to determine if using clay to test penetration would yield different results than meat. The experiment shot field and stone-tipped arrows from a compound bow fired from a bow tuning machine (Spot Hogg Hooter Shooter). This machine had a stand for mounting the bow and a ratchet mechanism that pulled the string back to the same draw length for each test, ensuring that equal pull force was used for every shot. The penetration depth of each shot was measured to the nearest millimeter and then statistically analyzed. Additionally, an Instron materials tester was used to measure the force required to cut meat and clay with razor blades. The results of these tests revealed that meat shows greater resistance to cutting and penetration from field points than does clay, but that it does not show significant differences when using stone points. This study concluded that clay was a close proxy for meat when firing stone points with a bow (Key et al., 2018).

As demonstrated by (Key et al., 2018), commercial potters clay has many properties that make it useful in projectile studies in place of meat when measuring penetration and is thought to be similar in response to ballistic penetration to glycerin soap (Coupland et al., 2011; Schyma, 2020). This is due to its plastic deformation when force is applied and its lack of elastic rebound after being cut. These properties allow for the preservation of the wound tract within the medium that can be further studied. However, it is important to note that the clay must be well-processed and homogenized in its matrix. Controls should be implemented to ensure the level of moisture and temperature, both of which can affect the resistance of the matrix, are maintained so that the results are consistent throughout the testing process. Likewise, scholars have noted that, when taking multiple shots into a single block, it is important to knead and work the clay between each shot to close off the previous wound tracts and smooth out any differential pressure in the matrix that was created by the impacts (M. I. Eren, personal communication, January 2021).

1.4 Objective

Of interest to our study is the difference in resistance force between four ballistics target materials. Due to the absence of comparative tests done on target media, as they pertain to low-velocity projectiles, it is essential to understand how various target materials compare to biological tissue. This study evaluates stone and steel points against the target materials: clay, ten and twenty percent ballistics gelatin, and meat, to assess the magnitude of force required to penetrate each material to a controlled depth using an Instron Materials Tester. The goal is to develop a baseline understanding of how the materials react during the penetration process for ongoing and future studies conducted at the Kent State University Experimental Archaeology Laboratory and others. This project will determine the comparative resistance of the two target materials: gel and clay, relative to biological tissue, i.e., meat. This will provide valuable data for how these materials compare under static testing which will inform future studies involving dynamic testing. The overall goal is to generate data that can be expanded with further testing to ultimately create a dataset that can then be referenced by all archaeologists and provide much-needed standardization in the field of experimental archaeology.

The null hypothesis of this study is: there will be no difference in the resisting force yielded by target materials, ten and twenty percent ballistics gel, potter’s clay, and biological tissue (meat), when penetrated by test projectile points. The broader implication of demonstrating that the null is true is that it will clarify the ongoing debate amongst archaeologists as to what material makes the most appropriate target for projectile testing by demonstrating that these materials all perform similarly.

The alternative hypothesis of the study is: there will be significant differences in resistance force yielded by target materials, ten and twenty percent ballistics gel, potter's clay, and biological tissue (meat), when penetrated by test projectile points. The broader implication of this result is that archaeologists will be able to modify their research designs so that they are using the target material most appropriate for testing arrowhead penetration efficiency.

Chapter 2: Methods and Materials

2.1 Methods

2.1.1 Experimental Design

This experiment explored the differences in resistance force of four target materials to two differing penetration implements. The target materials were 1) ten percent ballistics gelatin, 2) twenty percent ballistics gelatin, 3) commercial clay, and 4) butchered meat, with each of these pierced thirty times by a 1) stainless steel modern field arrowhead and a 2) manufactured stone point. The variation between the resistance forces would be difficult to detect without high precision and thus they were to be measured on a highly sensitive machine, and Instron materials tester, built specifically for this purpose. These measurements were then compared to each other to look for significant differences in the resistance force of the materials against the two points, as well as to show how the dissimilar materials compare to each other. These data give us a baseline understanding of how these target media respond to external piercing/cutting forces.

2.1.2 Target Material Selection

The materials chosen as target media are based on the majority of studies conducted by archaeologists to determine the penetration characteristics of different projectile point types. It is often assumed that ballistics gelatin is the best proxy for human tissue due to its use in tests conducted to understand penetration mechanics and wound tracking when a carcass or butchered meat cannot be used (see earlier). However, properly calibrated ballistics gelatin is both expensive and difficult to create in an archaeological setting, particularly for graduate students, and carcasses and butchered meat can create logistical and ethical hurdles. Commercial clay is considered a reasonable substitute when testing stone points as shown by Key et al (2018) and is used as a more financially, logistically, and ethically viable solution by many researchers, particularly at Kent State University.

2.1.3 Penetration Point Selection

Few archaeological studies concentrate upon the penetration mechanics of modern stainless steel field tip arrowheads; instead, often focusing on simulated or copied stone points or occasionally ancient styles of metal points. However, the emphasis of this study was to create a comparative baseline of resistance force measurements of the target materials. Therefore, one modern field tip and one copy of an ancient stone point were selected to demonstrate two opposing ends of the spectrum of materials that are often used in archaeological experiments. Both point types are symmetrically bladed and generally flattened into a single axis, thus having a similar shape while still displaying a disparate degree of material composition and technology, which would yield results that should be meaningful to most studies.

2.2 Test Design

To assess the resisting force of the study materials, ten and twenty percent ballistics gelatin, commercial clay, and butchered meat, the author used an Instron Universal Materials Tester (Model 5967) which could lower the point at a static rate into the targets while measuring the peak resistance force. The points were clamped to the upper, moving arm of the machine and aligned vertically above the target medium with the points in contact to, but not exerting any significant force against, the surface of the targets. The target materials were placed upon the lower pressure plate of the Instron which recorded the force magnitude exerted on the material sample during the duration of each test. (Figure 1). The machine then lowered the points at a rate of 0.1 mm per second over a span of 450 mm into the targets below, taking 7.5 minutes to run through one full penetration test. The ballistics gelatin and clay were both cut into roughly square blocks before being emplaced upon the pressure plate, while the meat was placed in a bowl to contain any liquids expelled during penetration.

Tests were started at a point at least 2 cm from the outer edge of the target material. After each penetration test was conducted, the material was shifted at least 2 cm away from the previous test parallel to the edge of the test material. The material aligned so that the successive tests would run parallel with the previous ones in the ballistics gelatin and commercial clay. Tissue fiber direction in the meat was not controlled for during the pilot study. Once one side of the material could no longer fit more test holes, it was to the opposite side.

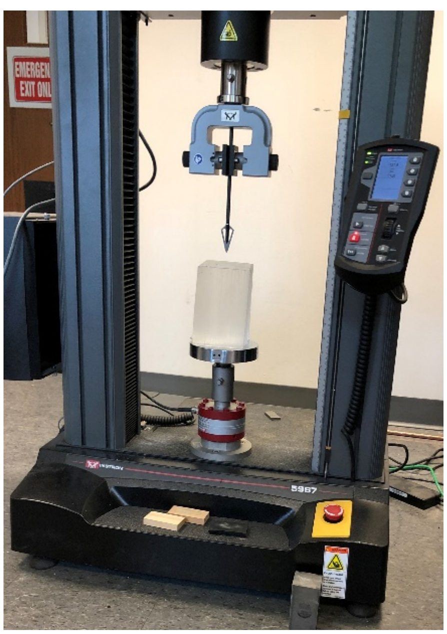

Figure 1: View of Instron setup.

2.2.1 Strength Measures Used in this Study

Maximum resistance force was recorded as the value defined here as "peak load", which was the maximum force applied during each test. The peak load was measured in Newtons.

2.2.2 Penetration Mechanics – Cutting and Crack Formation

When studying projectiles, many cite penetration as the most important factor in determining the lethality of projectile points (Kruse, 2010). Penetration is a result of the cutting action of the tip of the point into the target medium. Cutting itself is the propagation of cracks through a body of material, thus creating new surfaces that are exposed from within (Philip S. L. Anderson et al., 2016; Philip S. L. Anderson & LaBarbera, 2008; Phillip S. L. Anderson & Rayfield, 2012; Atkins, 2009). Cutting is the outcome of separation of the material into separate parts through the fractures created by the outward forces generated from the cutting implement, in this case in the form of a cutting wedge, as it moves through the material (Atkins, 2009). Different materials will display different elastoplastic (i.e., both elastic and plastic) fracture mechanics as an object moves through them, creating different deformation curves. Deformation curves can be J-shaped for stiff materials, linear for materials of a consistent matrix and resistance force, or parabolic for softer materials, or even sigmoid-shaped for elastic materials like rubber which are highly resistant to fracture, but propagate cracks quickly once a certain threshold, or yield point, is met (Atkins, 2009).

In this study, the materials were expected to react differently when the blades were forced into them. Each medium has substantially different material properties. For example, ballistics gelatin is an elastic material and first resists crack propagation by dissipating energy along its surface until enough pressure is applied to overcome that elasticity sufficiently to penetrate it. Once crack prorogation begins, the compressive deformation energy stored in the surrounding material will 'feed the crack,' at first reducing the amount of force required to continue expanding it. However, as the point continues through the matrix, the increasing drag further compresses the material matrix thus requiring additional energy to achieve further penetration (Atkins, 2009).

Commercial clay responds in a way similar to what Atkins (2009) describes as a "floppy material". Floppy materials show little to no elasticity resisting the penetrating force of the blade, so the energy required to slice through it falls on a generally straight line when graphed; increasing over time as the drag increases. As a cutting blade penetrates a floppy material, one or both sides of the incision become increasingly separated, resulting in an 'offcut' (Atkins, 2009). Offcut eliminates or reduces the amount of displacement force required to overcome drag created by elastic forces pushing back upon the surface of the blade (Atkins, 2009).

Meat responds in an analogous way to ballistics gelatin, though it is also somewhat 'floppy' like commercial clay as the sides can become slightly offcut during the process. Meat is generally less firm than ballistics gelatin and thus has more elastic resistance before crack propagation. It also has a reduced elastic rebounding force pushing back upon the cutting implement, resulting in less drag than in gelatin, which is further reduced by the moisture in the matrix lubricating against some of the friction (Atkins, 2009).

In penetration mechanics, all four target materials are considered soft compliant solids because they all behave in the same way after piercing, being globally elastic despite extensive deformation during penetration (Atkins, 2009); although the clay is much less so than the other two. In this instance, the sharpness of the blade plays a role in how quickly the cracks propagate in the skin of the material.

Another factor important to cutting mechanics is the speed at which the cutting implement is moving (Atkins, 2009). However, this study is focused upon the target materials and their resistance to cutting pressures by the penetrating points and not the cutting capabilities of the points themselves. Therefore, velocity was strictly controlled and eliminated as a variable, being reduced to a rate that was considered unlikely to affect

the cutting mechanics.

2.2.3 Pilot Studies in Archaeology

The purpose of experimental archaeology is to "furnish a foundation for explaining technological variation and change" (Schiffer et al., 1994, p. 198), creating strong theoretical principles that can be applied to test archeological hypotheses while rigorously following the scientific process (Marsh & Ferguson, 2010). To ensure that this project achieves a sufficient level of scientific reliability, it was conducted in two phases; First, a pilot study to evaluate the materials and methods that were to be employed; second an experiment conducted with procedures and guidelines established through the pilot study.

The importance of pilot studies in experimental archaeology has been enumerated by many researchers (Fish, 1978; Shennan, 2014; Wood & Fitzhugh, 2018a). This project strives to achieve internally valid measurements of the resistance force of the target materials. To do so, it is important to control as many variables as possible. However, despite these controls, unforeseen circumstances that arise during testing can still create disparities in the results. The current experiment, as outlined above, involves a highly calibrated machine created for experimental research, four target media, and two different projectile point types. Controlling the machine and point types was not a concern, as they are static insofar as how they perform during the test. However, I anticipated that two of the target materials might be more difficult to control and that their placement and the alignment of the tests might impact the overall performance of them after repeated probing. These concerns were the focus of the pilot study.

2.2.4 Issues Encountered During the Pilot Study

To determine the best practices and ideal conditions for conducting the penetration tests upon the target materials, I conducted a pilot project. I hypothesized that positioning the penetration tests too closely together or having too many on a single surface could cause the overall internal stability or external pressure of the matrix to degrade and thus create disparate measurements as the testing proceeded. While the reasons for this vary among the target media (material plasticity, elasticity, or changes to overall density), stability of the matrix throughout testing remained a possible source of inconsistent data that had to be considered and accounted for. Other concerns focused on the variations that would result from prolonged exposure to open air at room temperature for both the meat and commercial clay Clear Ballistics gelatin, however, is indefinitely stable at room temperature (*Clear Ballistics*, 2021). Further concerns centered specifically on the direction of the grain of the meat relative to the breadth of the projectile point during each test, which would likely affect the maximum force required, depending on whether the breadth of the blade ran parallel or perpendicular to the grain of the meat.

The pilot process demonstrated that test placement and open-air exposure did have a significant effect upon the maximum force tests for both the meat and clay media. When points of penetration were too close together, the materials showed less resistant force than when they were placed further apart; up to a point of about four centimeters between each test.

Air exposure produced additional issues. First, both the clay and meat warmed during the test. The pilot test showed that the clay showed more resistance when cold after arriving from the warehouse than after warming to room temperature (roughly 70 degrees Fahrenheit). Similarly, the meat, which was stored at 40 degrees Fahrenheit until testing began, warmed throughout the day to room temperature. However, not only did the shift to room temperature affect the results by decreasing the maximum force required to penetrate them but there were indications that the meat began to decay and show signs of tenderizing as the test continued. This increased the elasticity of the matrix due to fiber degradation while decreasing the maximum force required to penetrate it (Figure 2). It was also noted that grain direction running either parallel or perpendicular to blade breadth affected the resistance force encountered during penetration.

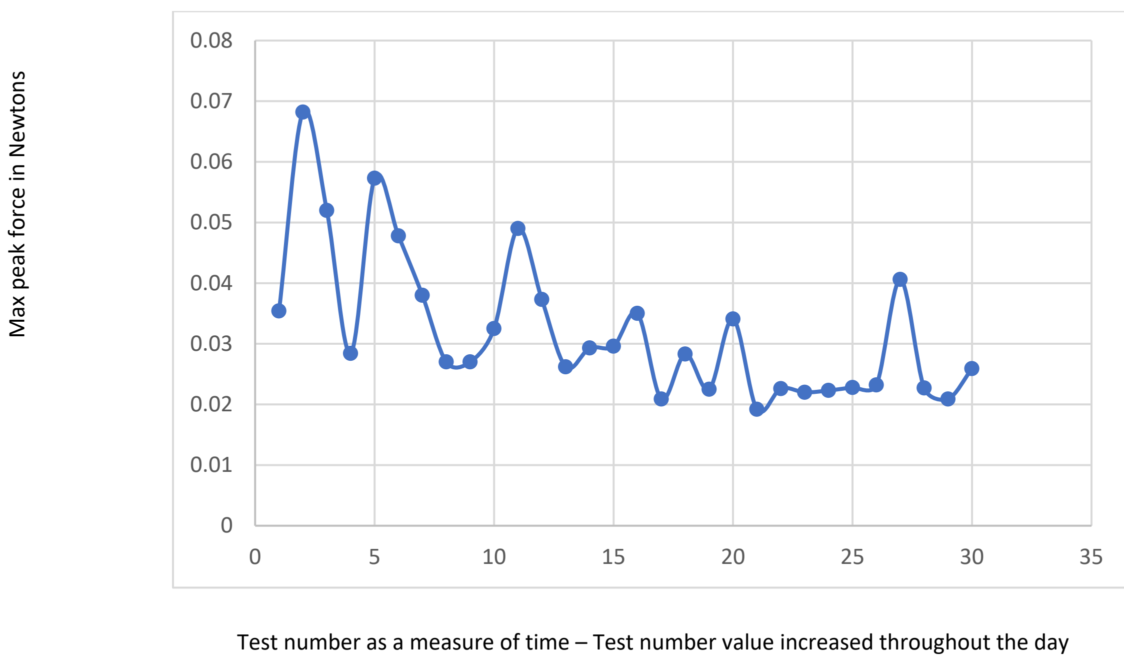

Figure 2: Graph of tests of the stone point into the meat over time showing how the resistance decreased due to decay and a tenderizing effect.

2.2.5 Actions Taken to Address Issues from Pilot Study

To address these concerns, the test procedures were modified as follows. First, the puncture points were moved further apart to at least four centimeters from each other and the edge of the target material. Puncture placement had less effect upon the gelatin target than on the meat or clay targets, but protocols were nevertheless adjusted so that all materials were treated equally.

Next, new commercial clay was purchased that was more recently processed and kept at room temperature with the moisture monitored using a soil moisture monitor both before and during testing. The clay was then forcefully compressed between puncture test runs to close the holes created by the penetrating points. This process is the same as what is during dynamic tests in the lab at Kent State University. It has been to diminish the offcut effect mentioned above and keep the uniformity of the material intact (M. I. Eren, personal communication, January 2021). This resulted in more consistent results across all of the tests in the clay.

The butchered meat used as target material during the second phase of testing was beef "eye of round" roast (as opposed to the first cut of a "beef bottom roast"). The "eye of round steak" comes from the elongated muscle in the rear leg area of the cow, which is used for movement and thus leaner and tougher, which was expected to help combat the tenderizing effect encountered previously. In contrast, the "beef bottom" or "rump roast" is cut from the hindquarter that covers the hip bone and made up of three separate muscles that do little work, resulting in a mixture of textures and tenderness (Gerrard, 2021). The butchered meat was kept at 40 degrees Fahrenheit in a refrigerator until each experiment began. Each section of butchered meat was placed into a plastic container and then pierced by the Instron 6-8 times depending on the size of the roast. In toto, eight “eye of round” roasts were used. Given that each puncture test took 7.5 minutes to complete, each roast was exposed to the room temperature of 70 degrees Fahrenheit for approximately one hour. Overall, there was very little change in the meat during the second round of experimental tests due to the decreased exposure to room temperature along with the increased spacing (>4 cm) between the arrow punctures into each roast. In addition to increasing the distance between punctures, only one side of the meat was used for puncture tests during the second phase. Additionally, each puncture was set up so that the arrow point punctured the meat at an angle perpendicular to the prior puncture. In total there were fifteen punctures “with the grain” and 15 punctures “against the grain”.

2.3 Materials

2.3.1 Ballistics Gelatin

To ensure that the ballistics gelatin used would be homogenous and consistent with FBI and NATO practices and to avoid the gelatin drying before testing, synthetic, shelf-stable, commercial gelatin was purchased from Clear Ballistics in Greenville South Carolina. Tests were conducted with 10% and 20% gelatin concentrations, both of which the company calibrates following FBI protocols (Figures 3 & 4).

Figure 3: Manufactured stone tip penetrating ballistics gelatin during the pilot project.

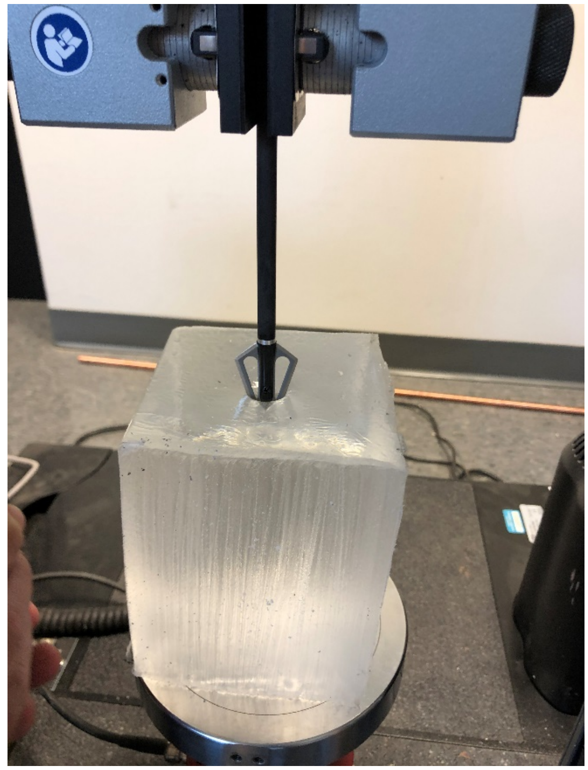

Figure 4: Modern field tip penetrating ballistics gelatin during the pilot project.

2.3.2 Commercial Clay

Like the ballistics gelatin, the clay target medium was chosen for its homogenous consistency. The specific material used was fresh Standard #103 potter's clay purchased from Ohio Ceramic Supply in Ravenna, Ohio. The clay was allowed to warm to room temperature before testing began and was kept covered in plastic to maintain moisture during testing.

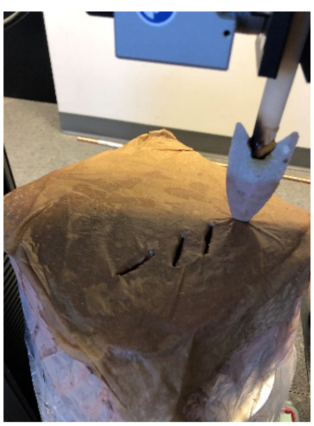

Figure 5: Stone point penetrating clay block as part of the pilot project. The holes were aligned parallel in the project tests and the material massaged to close the offcut created by the test probes.

2.3.3 Butchered Meat

Butchered meat was purchased at local grocery stores in Kent, Ohio. As mentioned above, the meat chosen was “eye of round beef”. This particular cut was selected because its shape minimized the horizontal plastic deformation that occurred during the puncturing of the target. Each piece was inspected based on how much intramuscular fat or connective tissue was visible to limit their effects as much as possible.

Figure 6: Penetration of field tip into the meat during the pilot study. Note the lack of stability in the matrix and the tenderizing effect of the continuous testing.

Figure 7: View of the stone tip penetrating the meat in the pilot study. Note the line of intramuscular fat bisecting two of the muscles.

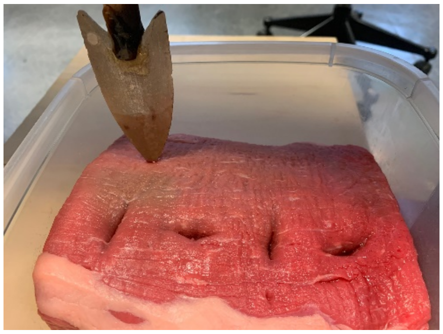

Figure 8: Stone point penetrating meat during the project experiment. Note the stability of the matrix as well as the shifting of the direction of the penetration probes to avoid biases created by the meat grain.

2.3.4 Modern Point

To represent a modern point type, a Stinger Broadheads 100 GR 2 blade stainless steel broadhead field tip was fitted to a 100% carbon Blackout X5 Envy shaft cut to 16.3 cm in length.

2.3.5 Stone Point

To ensure the stone point had a consistent shape that would be both smooth and symmetrical to avoid creating extra drag or resistance along the flake scar ridges, a ground lanceolate stone projectile point was used as opposed to a flint-knapped one. The stone points were produced by Neolithics Flintknapping Supply House (www.neolithics.com) using Texas Fredericksburg chert. They were created by first cutting slabs of chert with a rock saw, putting the slabs into a kiln and heat-treating them to 450°, then drawing a pattern for each particular point shape on the slabs and cutting them out with a trim saw. Next, each point-shaped slab was rough ground with a 30-grit diamond wheel followed by a 60-grit diamond wheel to produce a typical stone tip's lenticular shape. The points were then fitted onto a 13.5 cm length of ½ in (1.27 cm) thick poplar dowel rod and secured using Bohning Ferr-L-Tite adhesive.

Figure 9: Modern steel field tip and manufactured ground flint tips mounted to their respective shafts.

Chapter 3 - Results

This experimental study evaluates the mean maximum resistance force, measured as peak load (kN), of four materials; ten and twenty percent ballistics gelatin, commercial clay, and butchered meat, against two penetrating objects; a modern steel field arrowhead and a commercially manufactured, ground-stone point.

The peak load measuring the max penetration force is the dependent variable, while the target materials are the independent variables. The test was conducted at a significance of 95%. The null hypothesis, signified by a non-significant result (<.05), is that all of the materials will resistance penetration equally. A significant result (>.05) means that there was enough variation between the resistance forces to reject the null hypothesis. The mean, minimum, maximum, and standard deviations of the max values for each test are listed in Table 1.

Table 1: Descriptive statistics for both the pilot and project data.

Phase	Point	Material	Minimum Resistance in Newtons	Mean Resistance in Newtons	Maximum Resistance in Newtons	SD of Resistance in Newtons
Pilot	Steel	10% Gel	0.0113	0.0128	0.0138	6.2639E-04
Pilot	Steel	Clay	0.0189	0.0252	0.0318	3.9280E-03
Pilot	Steel	Meat	0.0069	0.0125	0.0193	3.0770E-03
Pilot	Stone	10% Gel	0.0274	0.0316	0.0351	2.5366E-03
Pilot	Stone	Clay	0.0364	0.0435	0.0542	4.8761E-03
Pilot	Stone	Meat	0.0192	0.0323	0.0682	1.2095E-02
Project	Steel	10% Gel	0.0130	0.0135	0.0140	5.0855E-04
Project	Steel	20% Gel	0.0190	0.0219	0.0230	9.7809E-04
Project	Steel	Clay	0.0130	0.0156	0.0180	1.3817E-03
Project	Steel	Meat	0.0150	0.0207	0.0280	3.2921E-03
Project	Stone	10% Gel	0.0310	0.0352	0.0421	2.8781E-03
Project	Stone	20% Gel	0.0550	0.0613	0.0650	2.7535E-03

Project	Stone	Clay	0.0320	0.0443	0.0600	8.3907E-03
Project	Stone	Meat	0.0310	0.0616	0.0780	1.2043E-02

3.1 Statistical Analysis

3.1.1 Normality

As mentioned, the experiment was conducted twice. The first time as a pilot project and the second with changes to the procedure based on lessons learned in the pilot study. Tests for normality showed that most of the test results were non-normal (see Table 2 and Figures 14-27 in appendices), therefore, non-parametric Kruskal-Wallace tests were used to determine if the variation between the studies and the material types was statistically significant.

Test	Point Type	Target Medium	Skewness	Z-Score (@ SE Skewness = .427)	Kurtosis	Z-Score (@ SE Kurtosis = .833)	Kolmogorov-Smirnov	Shapiro-Wilk	Result @ $p < .05$
Pilot	Steel	Gel (10%)	-0.365	0.46	-0.349	0.30	0.097	0.378	Normal
		Meat	0.635	**3.05**	0.092	0.12	0.105	0.094	**Non-Normal**
		Clay	-0.010	0.02	-1.145	0.58	0.200	0.175	Normal
	Stone	Gel (10%)	-0.193	0.31	-1.337	0.62	0.104	**0.033**	**Non-Normal**
		Meat	1.392	1.44	1.587	**2.10**	**0.009**	**0.001**	**Non-Normal**
		Clay	0.765	**2.26**	-0.268	0.24	0.144	**0.029**	**Non-Normal**
Project	Steel	Gel (10%)	0.000	0.00	-2.148	0.72	**0.000**	**0.000**	**Non-Normal**
		Meat	0.496	**7.19**	-0.459	0.36	0.200	0.253	**Non-Normal**
		Clay	0.188	0.79	-0.861	0.51	0.051	0.051	Normal
		Gel (20%)	-0.829	0.66	-0.111	0.12	**0.000**	**0.001**	**Non-Normal**
	Stone	Gel (10%)	0.615	**3.27**	0.220	0.36	0.102	0.134	**Non-Normal**
		Meat	-0.791	0.65	4.148	1.25	0.094	0.066	Normal
		Clay	0.319	**2.95**	-1.108	0.57	0.200	0.105	**Non-Normal**
		Gel (20%)	-0.829	0.66	.0125	.018	0.200	**0.011**	**Non-Normal**

Table 2: Normality results based on multiple tests for both the pilot and project data.

3.1.2 Stone vs Steel

Mann-Whitney tests between stone and steel point types on each medium yielded significant results at $p < .001$, however, both the pilot study and the project tests show patterning in the variation between the two (Figures 10 and 11.

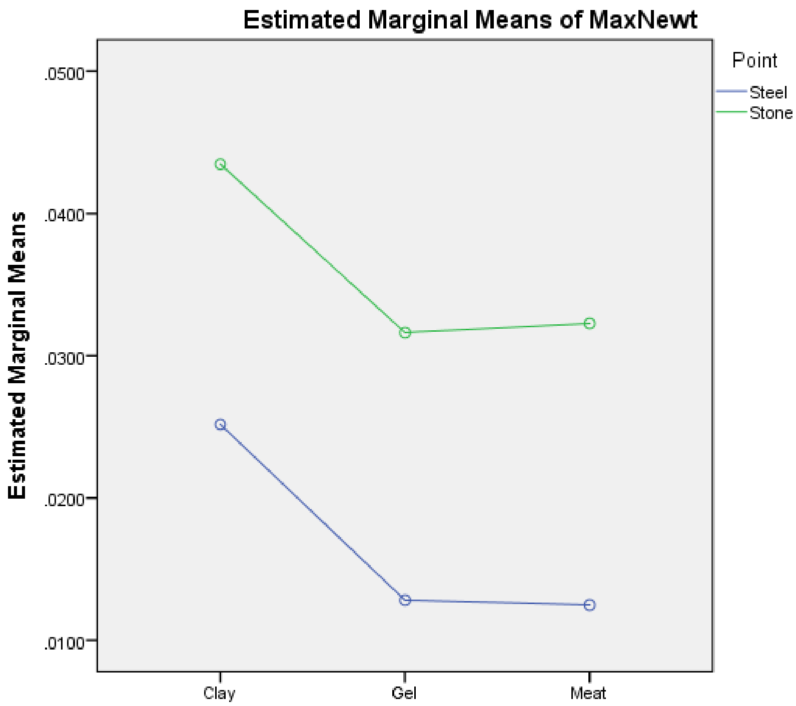

Figure 10: Graph of mean max resistance forces displayed by each material for each point type during the pilot study.

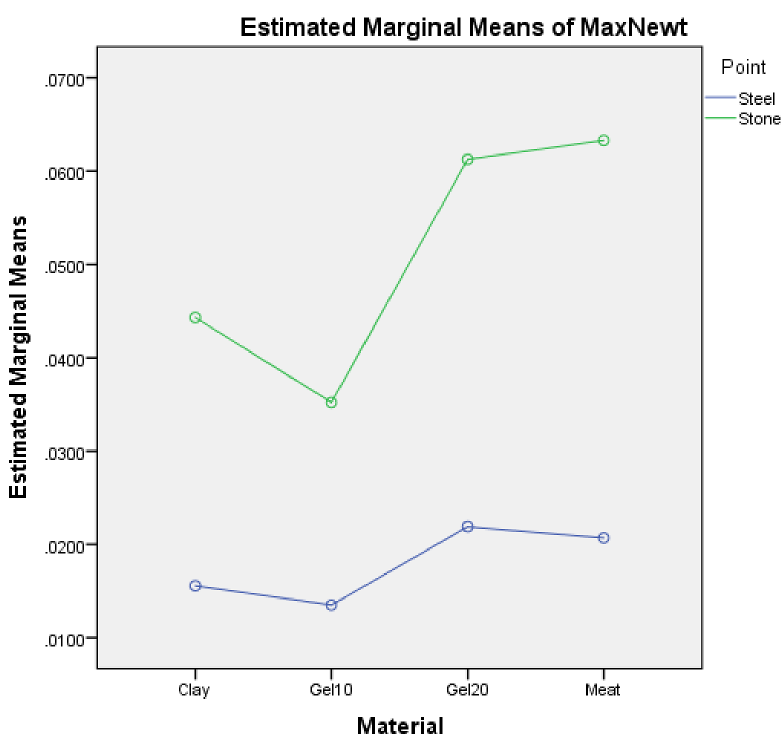

Figure 11: Graph of mean max resistance forces displayed by each material for each point type during the project.

3.1.3 Tests Between Target Media

Tests between target media in the project data yielded significant differences between clay and meat, clay and 10% gelatin, clay and 20% gelatin, and 10% gelatin and meat for both point types at $p < .001$ for all. Tests between 20% gelatin and meat yielded significant results for steel arrows at $p = .040$, while the test between 20% gelatin and meat were non-significant at $p = .284$ (Table 3), indicating that the difference in the peak load between the two materials was not significant.

Point	Test	p-Value	Variation
Steel	10% Gel vs Meat	0.000	Significant
	Clay vs Meat	0.000	Significant
	20 % Gel vs Meat	0.040	Significant
Stone	10% Gel vs Meat	0.000	Significant
	Clay vs Meat	0.000	Significant
	20 % Gel vs Meat	**0.284**	**Non-Significant**

Table 3: Significance of variation between target media during the project study.

Box plots show that, despite there being only one non-significant result, that of 20% ballistics gelatin and meat, there was a wide range of test variation found within the meat, and this variation overlaps all other target materials and their ranges during the testing, particularly when using stone points. Also notable is that, while a non-significant difference in range of variation exists between 20% gelatin and meat, the low variation of the results of the gelatin is drastically more narrow than that of the meat. (Figures 12 and 13) which suggests it may be *too* consistent to be an accurate proxy for measuring penetration.

Figure	Point	Material	Minimum Resistance	Mean Resistance	Maximum Resistance	SD Resistance
12	Steel	10% Gel	0.0130	0.0135	0.0140	5.0855E-04
12	Steel	20% Gel	0.0190	0.0219	0.0230	9.7809E-04
12	Steel	Clay	0.0130	0.0156	0.0180	1.3817E-03
12	Steel	Meat	0.0150	0.0207	0.0280	3.2921E-03
13	[illegible]	[illegible]	0.0310	0.0352	0.0421	2.8781E-03
13	[illegible]	[illegible]	0.0550	0.0613	0.0650	2.7535E-03
13	Stone	Clay	0.0320	0.0443	0.0600	8.3907E-03
13	Stone	Meat	0.0310	0.0616	0.0780	1.2043E-02

Range = 0.0130 – 0.0280

Table 4: Mean, Range, and Standard Deviations of project tests.

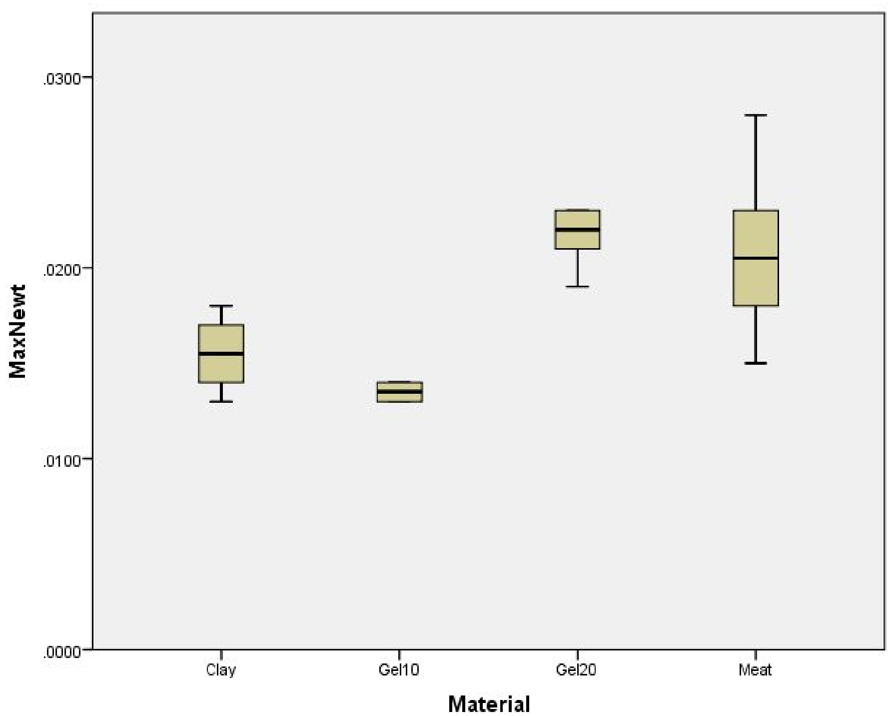

Figure 12: Box plot of results of project data for the modern steel field arrowhead.

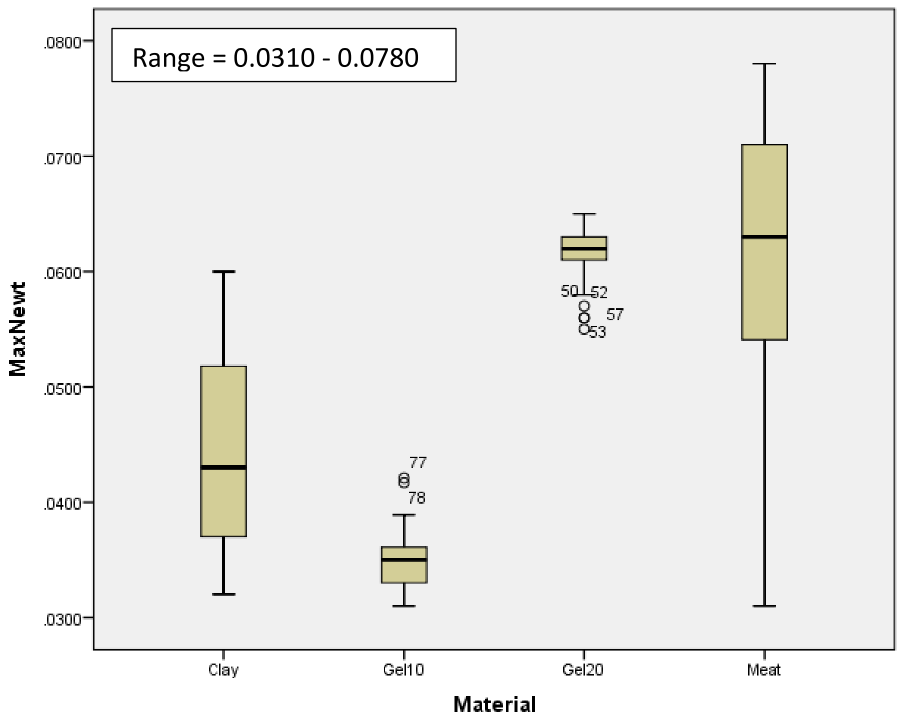

Figure 13:Box Plot of results of project data for manufactured stone points.

Chapter 4 – Discussion

The objective of this study was to understand the variation between the four target test media, ten and twenty percent ballistic gelatin, potter's clay, and butchered meat. The results indicate that the best, statistically analogous proxy for butchered meat in penetration tests with projectile points is 20% ballistic gelatin. The results also indicate roughly similar patterns of penetration resistance between modern steel and manufactured stone points in each medium, with clay being the most consistent among them.

However, several other notable results require consideration. The first of these is the vast variation in maximum force resistance found in butchered meat, particularly when using stone points. Meat is a highly inconsistent material when compared to commercial clay and ballistics gelatin. Sinew, fat, and grain direction of the muscle when pierced can all affect the resistance force encountered by a penetrating point. This is in stark contrast to both ballistics gelatin and clay, which are both more homogenous materials. The fact that the resistance of both these materials fall within the resistance variation of meat indicates that, depending on what level of external validity is being sought, any of the materials tested here may serve as a reasonable proxy for some biological tissue.

Further evaluation shows that both the 10% and 20% ballistics gelatin are so homogenous and consistent that they have an extremely narrow range of variation (0.0134 to 0.0140 for steel points in 10 % gelatin, 0.0190 to 0.0230 in 20%; 0.310 – 0.421 for stone points in 10 % gelatin and 0.0550 to 0.0650 in 20%) and may only be reliable proxies for meat under specific circumstances where the *precision* of the maximum resistance force is crucial. Thus, while 20% gelatin is not statistically significant in resistance force when compared to meat, its reduced window of variation is much smaller than that of meat and may effectively make it less externally valid than clay, which, though it often has lower mean resistance, shows a similar range of resistance that overlaps with meat and still falls within the lower threshold. These results, despite indicating a significant difference between clay and meat, should be seen as an indication that the findings of Key et al. (2018), who observed that, during controlled dynamic projectile tests, clay could be used as a simulation of meat, were valid; accepting that the velocity of the projectile, intentionally and effectively eliminated in this study but not in theirs, could be one explanation of their results being significantly similar while these were not.

Other observations to note are the disparity between 10% ballistics gelatin and all other materials. These results indicate 10% gelatin may be the worst proxy for meat in projectile point tests, supporting the observations made by Karger et al. (1998). Not only are the mean resistance force measurements lower than all other test materials, but the reduced window of variation means that it will only yield results that fall along the lowest possible threshold for butchered meat with only minimal variation. As with other media, the question that is being asked will ultimately determine which material to use. For example, tests to understand wound volumes may see clay as a more useful medium, while ballistics gelatin or, more likely, butchered meat, would be a more suitable material if tissue reaction to wounding were the focus of the study. Nevertheless, it stands that the prohibitive cost and lack of consistency among archaeologists to properly calibrate the gelatin in tests make it less attractive simulant than clay or even butchered meat, which can have logistical restrictions.

Finally, it must be restated that butchered meat is a highly variable test medium that itself could be further investigated for differences based on species, cut and orientation of muscle, degradation time, overlying pelt, etc. While it is arguably the most externally valid approximation of piercing living muscle, it is still deficient as a proxy for a live or cadaverous body. Butchered meat lacks the bones, empty cavities and variations created by organs and other tissues, the dynamic flexion of muscles when hit by a point, and the lubricating effects of blood upon the penetration mechanics. While large portions of meat containing bones and sinew can be purchased and modifications to procedures implemented to increase reliability, it will never be a fully externally valid medium for testing the penetration mechanics of projectile points. Further complicating the use of meat is its ongoing decomposition at room temperature that can only be offset with freezing and then thawing the meat for testing, which then affects its performance at a cellular level (Leygonie et al., 2012). This again supports the results of Key et al. (2018) of clay as the most cost-effective, logistically efficient, and similarly mechanically variable material to butchered meat for use in internally valid experiments.

4.1 Limitations of Experiments, Importance of Isolating Variables, and Understanding Interactions

Different test media yield distinct results. This is one of the many reasons to isolate variables and test them relatively so that disparities can stand out and specific factors that are not affected by the variation can be studied. Penetration in clay or gel may not be the same as in flesh, but the relative differences in a consistent medium can yield results of relative effectiveness. Furthermore, understanding the interactions between the points and the target media is imperative when planning future studies.

This is also true for the penetration force, as it demonstrates the properties of the arrow tips in various media and shows us if those media exert different forces that make the results in clay or gel invalid versus meat. Of course, none of these media can simulate a true, living body and therefore results are based on controlled isolation of variables. Field tests may be the ultimate form of experiment, yielding maximum external validity, but they suffer from difficulties in understanding how variables interact and can create ethical issues.

4.2 Applications of Existing Experiments

A related consideration should be made towards the study conducted by Courtney et al. (2017) that concluded that penetration tests in Clear Ballistics gelatin resulted in depths that were significantly greater than regular standard ballistics gelatin. Several factors are important to consider here. First, the study in question was a conference paper and never published in a peer-reviewed journal. The sample size is small, and few statistics are given. The authors claim that Clear Ballistics gelatin had lower retarding forces, erratic expansion, greater variation in penetration, and greater overall penetration than 10% FBI gelatin. Even if this were the case, none of these factors would affect the results of the current study other than the possibility that the overall resistance of the gelatin may be lesser than 10% FBI gelatin. However, even this scenario becomes moot when considering that the speed at which a bullet travels is so exponentially faster and their forms so drastically divergent than hafted projectiles, that their behavior when striking a target is completely different. Regardless, because of the possible variation suggested by Courtney et al. and to expand the data generated by this experiment, a fourth material, Clear Ballistics 20% gelatin, was added. Not only should the extra density of the matrix slow the projectiles more than the 10%, thus compensating for the differences suggested by the authors, but it adds another dimension to the project by including a material that has been tested by others in the past against the 10% ballistics gelatin using firearms (Carr et al., 2018; Coupland et al., 2011; Fackler & Malinowski, 1985), but never, to this author's knowledge, with projectile points.

This study focused upon the relative resistance between the four materials to understand their characteristics and ability to substitute each other in hafted-point penetration studies. While a study comparing the responses of 10% FBI calibrated gelatin to Clear Ballistics gelatin could be meaningful, it is beyond the scope of this experiment in both cost and purpose.

Another consideration worth noting regards concerns about whether or not meat that has been frozen exhibits the same resistance mechanics as meat that has been butchered but not frozen. As noted above, freezing meat changes its cellular structure and tenderizes it, thus reducing the force required to shear it (Leygonie et al., 2012). However, this study was focused on comparing ballistics gelatin with clay and meat, which was considered to be the most externally valid material. The meat chosen was selected as a practical proxy that could reasonably be obtained by a team with time, logistical, and cost constraints. Butchered meat, whether frozen or not, is not a perfect surrogate for a living organism (see above), and so the meat chosen for this project was based more on expected limiting factors in a lab setting than on external validity.

4.3 Bullets vs. Projectile Points – Different Penetration Mechanics and Velocities

As mentioned above, the penetration mechanics of bullets are drastically different from those of projectile points for several reasons. First, bullets are often a round or cylindrical shape that is tapered towards the nose and ends in a rounded head, a flattened head, or a concave pit, like those of hollow-point bullets. Arrow and stone points, except ground wooden, bone, bodkin, or other specialized styles, are shaped as chisels in terms of their cutting mechanics when slicing into a target medium (though some bodkins are also shaped as chisels as well).

Bullet penetration and wounding are based upon the concussive forces created by the impact with the material and the cavitation fractures that tear the target medium apart not only along the trajectory of the bullet but all around it as well. Point projectiles, on the other hand, cause little concussive force and no real cavitation damage.

Furthermore, some bullets are designed to break apart upon impact with the target body, thus fracturing into multiple pieces of shrapnel that tear into the target medium, creating multiple wound tracts. Other forms of ammunition, like shotgun pellets, are scattered as soon as they leave the chamber of the gun, creating a similar, if much more widespread, effect. Modern arrow points are not designed this way, though some are made to spread open upon contact with a target. And while studies show that some ancient stone points were intended to break upon impact (Michelle Rae Bebber et al., 2017; Mika et al., 2020), most arrows are designed to create a single wound tract that follows the path the point took while entering the body.

Finally, the most significant difference between the penetration mechanics of bullets and arrow or other point types is the velocity that the projectile is traveling. Bullets travel at an exponentially higher rate than a mechanically thrown or fired projectile, so much so, that they can exhibit non-Newtonian behavior when fired into ballistics gelatin (Subhash et al., 2012). Velocity is known to affect the penetration mechanics of the fired object when it comes in contact with a target material (Atkins, 2009; Coupland et al., 2011) and the vast difference between the velocity a bullet travels at compared to an arrow creates a disparity in the penetration mechanics that should preclude any results that show target material behavior with bullets from being meaningful when wanting to understand how those materials perform against arrows and other projectile points.

Conclusion

The goal of this study was to develop an understanding of the mechanical variation found between different target media often used for penetration experiments. To do so, I evaluated the variation between four different target materials using two different point types that encompassed divergent levels of penetration resistance due to point material type and overall morphology. The results revealed that two of the media, 20% ballistics gelatin and meat, have statistically similar resistance to force when punctured with stone points. In contrast, the results show that statistically significant variation exists between all other target materials. This indicates that, as far as resistance force is concerned, only the 20% ballistics gelatin showed non-significant variation with meat only when pierced with a stone point. However, the results have also shown that, though some materials may not have mean resistance force measures within the parameters of meat, their ranges are still within the broad range of variation that it encompasses and thus, depending on the question being asked, are internally valid media for testing penetration and wounding patterns of projectile points.

These results are the starting point to further experiments that will be conducted to understand how these materials perform under lab conditions when used for penetration studies. Future research will include dynamic testing of the same four target materials which will involve firing the projectiles from a stationary launch point at controlled velocities. This will assess the variation introduced by the velocity of the penetrating object upon the cutting force of the projectile in the target media, which will then lead to further dynamic studies of penetration and wounding properties of various point typologies.

Perhaps the most important takeaway from this study is that the best target medium to use is dependent both upon the questions being asked and the internal or external validity sought. While these data indicate that the best medium for penetration resistance testing at extremely slow velocities is 20% Clear Ballistics ballistics gelatin, this is a highly controlled example and only indicative of the procedures followed for this specific experiment. Most important in this case is the velocity of the cutting mechanism, which can be influenced in other types of tests and may affect the overall performance of the materials against the points when velocities are increased.

Nevertheless, the results of this study show that for internally valid tests that yield consistent results within the mean maximum resistance force of meat during static testing, then calibrated 20% ballistics gelatin is the best material to use. However, a key takeaway, relevant to all archaeological penetration studies is that, unless the researcher is seeking highly precise static penetration resistance force measurements along the lower boundary of meat, 10% ballistics gelatin is the worst approximation for butchered meat. Likewise, it is important for those conducting experimental penetration studies to report both the recipe and percentage of gel they have produced. Indeed, as demonstrated here, 10% ballistic gel is the least accurate proxy for biological tissue and therefore could be generating inaccurate measures of projectile point penetration efficiency.

Given the cost of purchasing 20% ballistics gel and the difficulty of making it oneself, I conclude that if the experiment seeks to mimic the range of variation found in meat in static testing, while still yielding results within the lower bounds of the mean maximum resistance force, then commercial clay is the most similar material to the variation found within meat while also being the most logistically simple to work with and also offers cost-effectiveness.

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https://doi.org/10.1016/j.jas.2017.10.006

Appendices: Figures

Figure 14: Pilot Study: Steel in 10% Gel Histogram

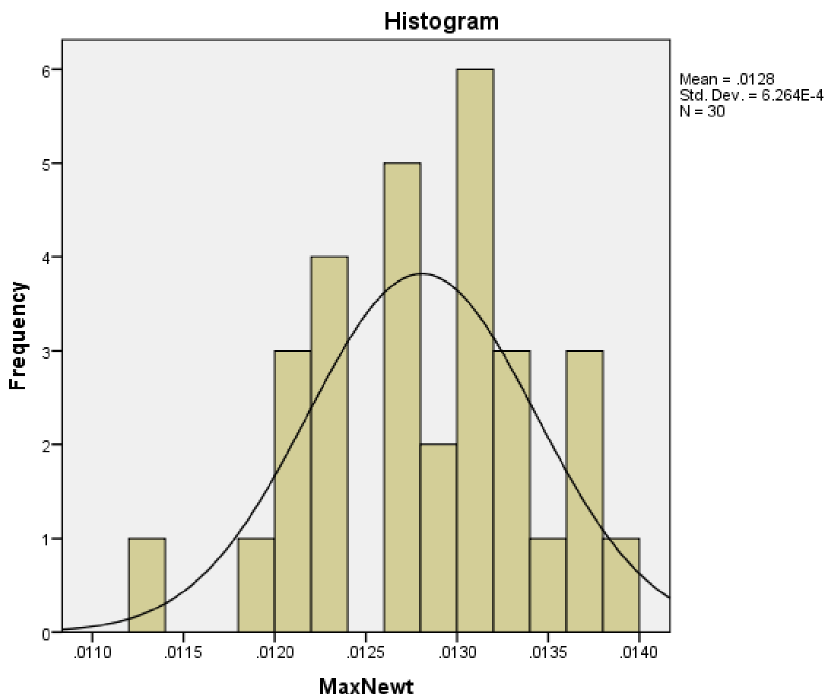

Figure 15: Pilot Study: Steel in Meat Histogram

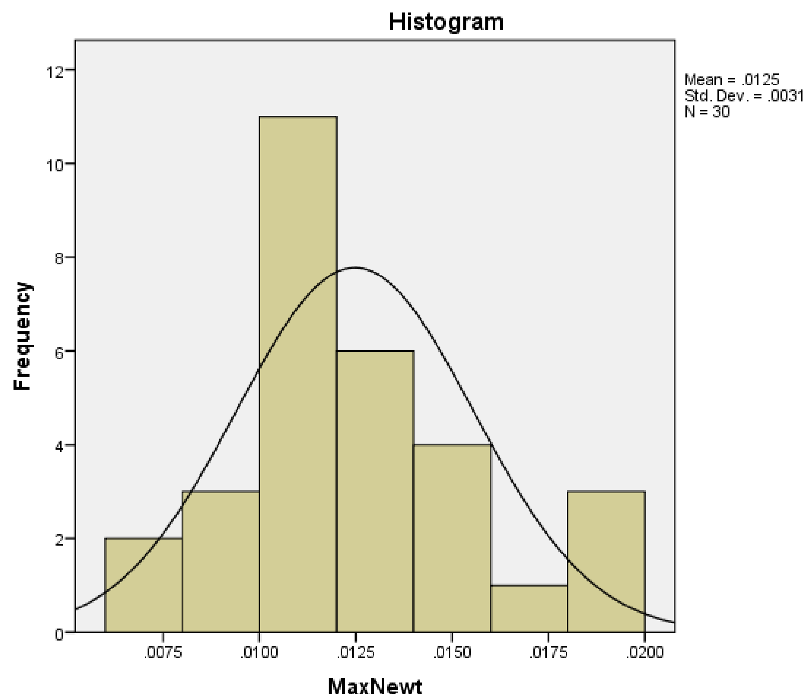

Figure 16: Pilot Study: Steel in Clay Histogram

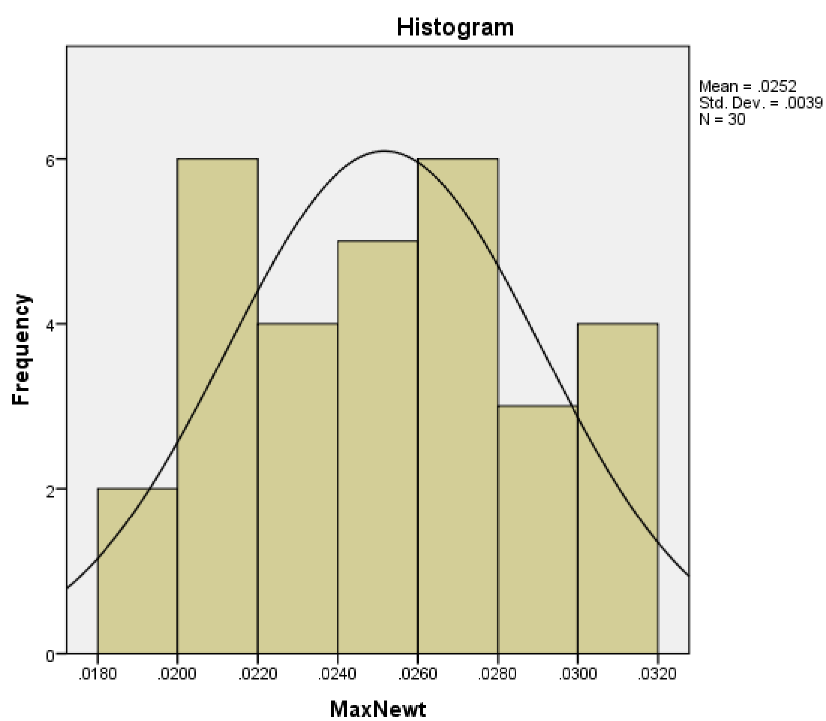

Figure 17: Pilot Study: Stone in 10% Gel Histogram

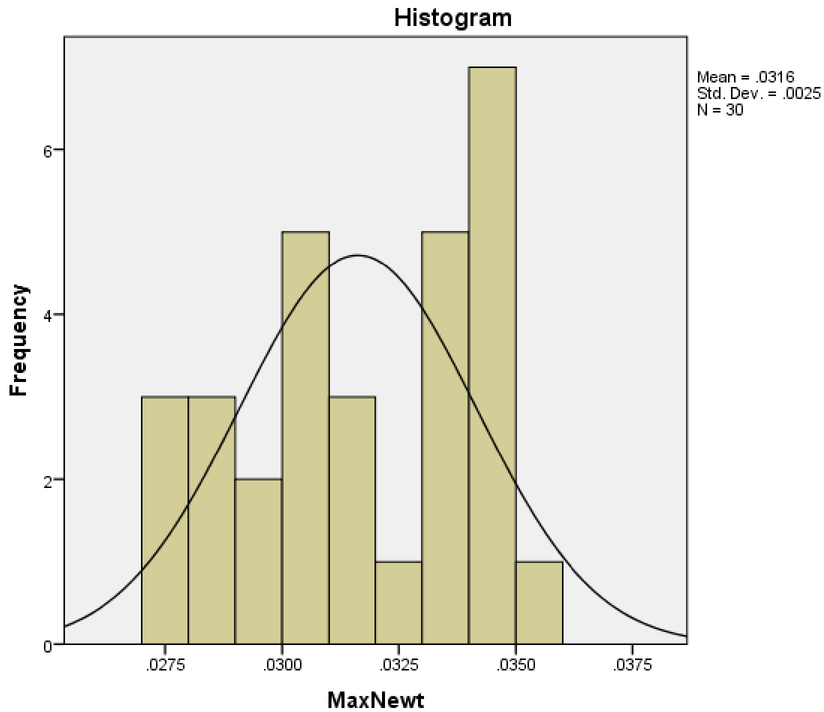

Figure 18:Pilot Study: Stone in Meat Histogram

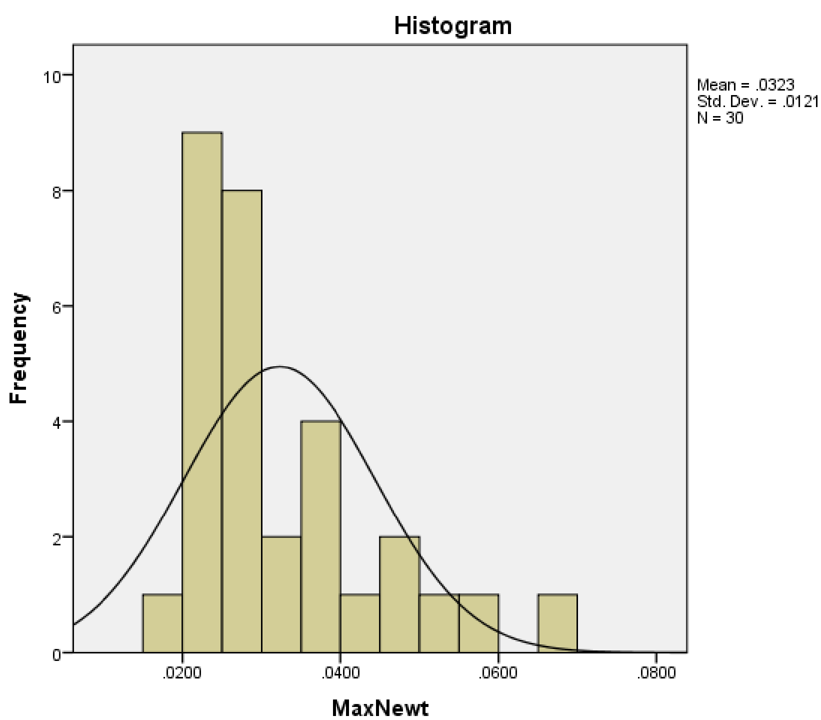

Figure 19: Pilot Study: Stone in Clay Histogram

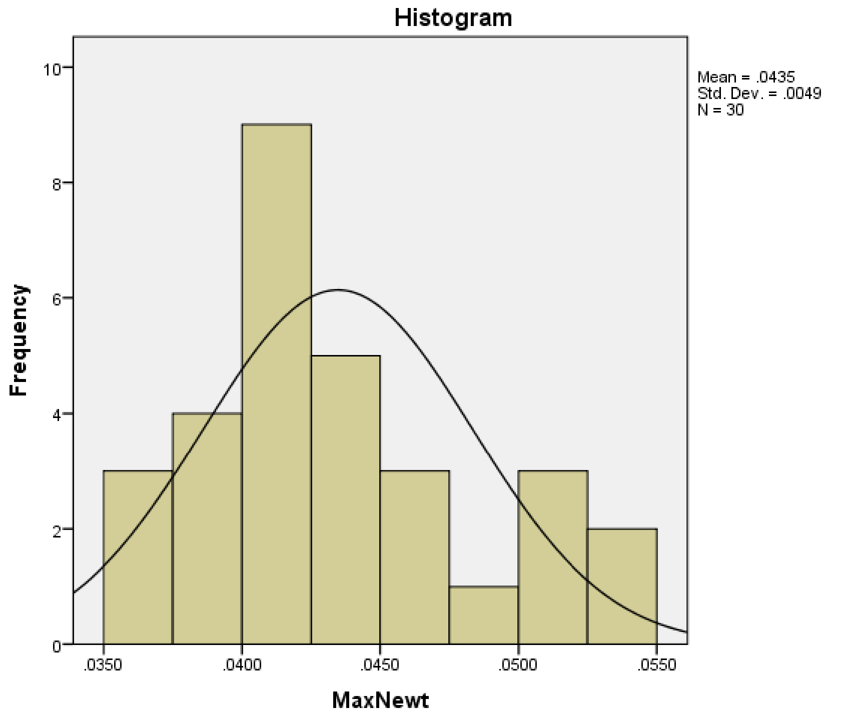

Figure 20: Project Study: Steel in 10% Gel Histogram

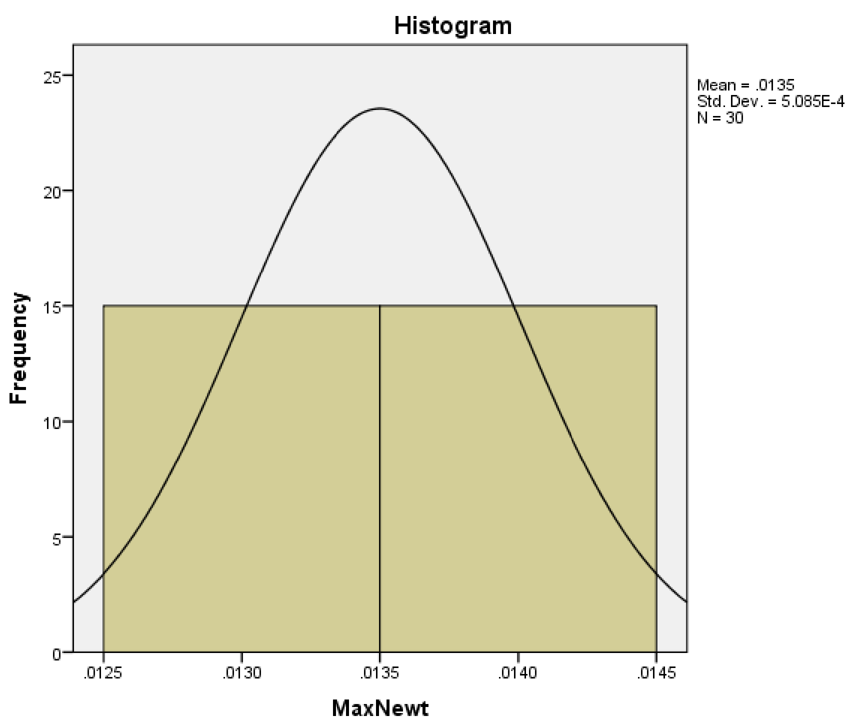

Figure 21: Project Study: Steel in Meat Histogram

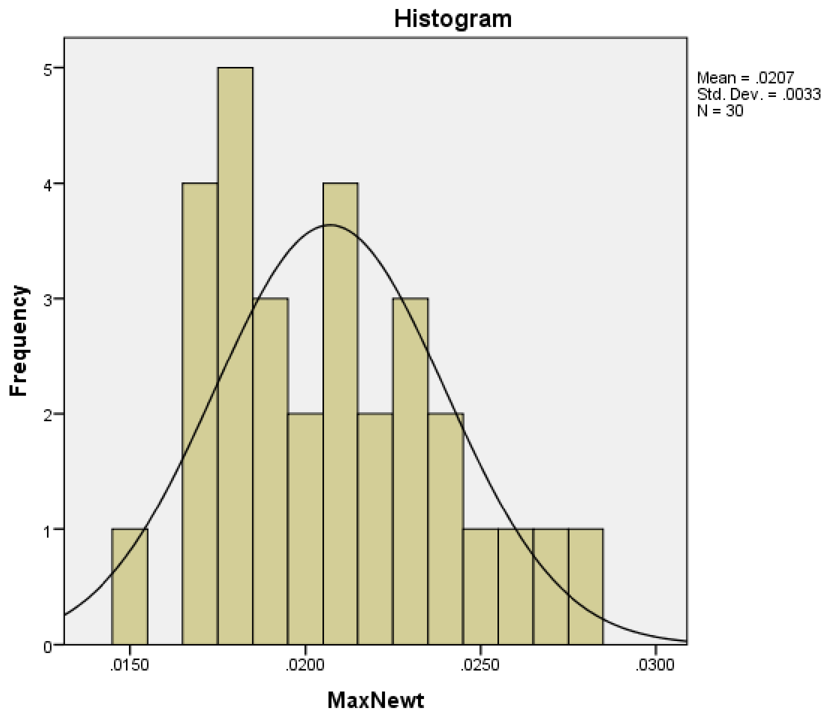

Figure 22: Project Study: Steel in Clay Histogram

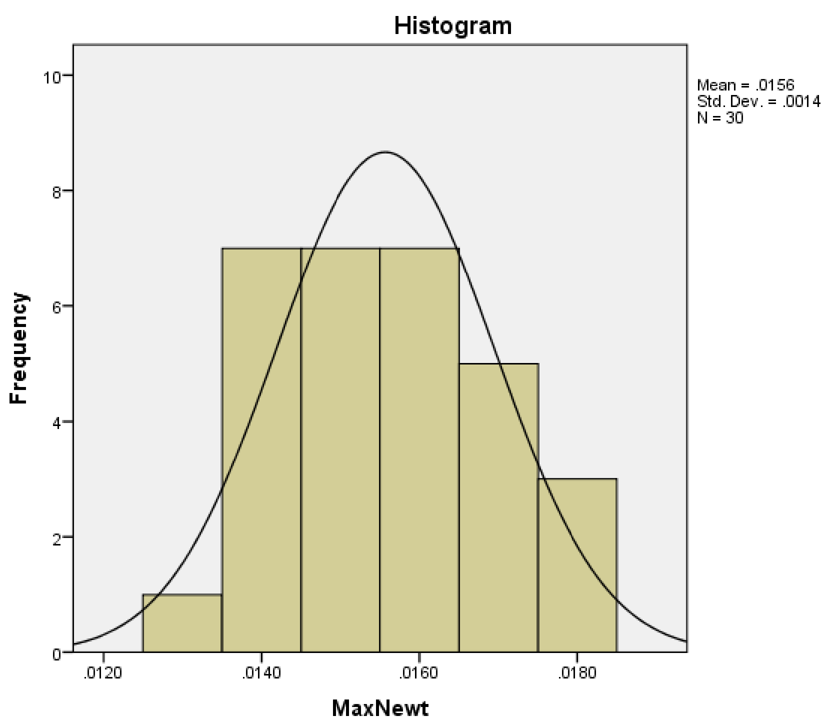

Figure 23: Project Study: Steel in 20% Gel Histogram

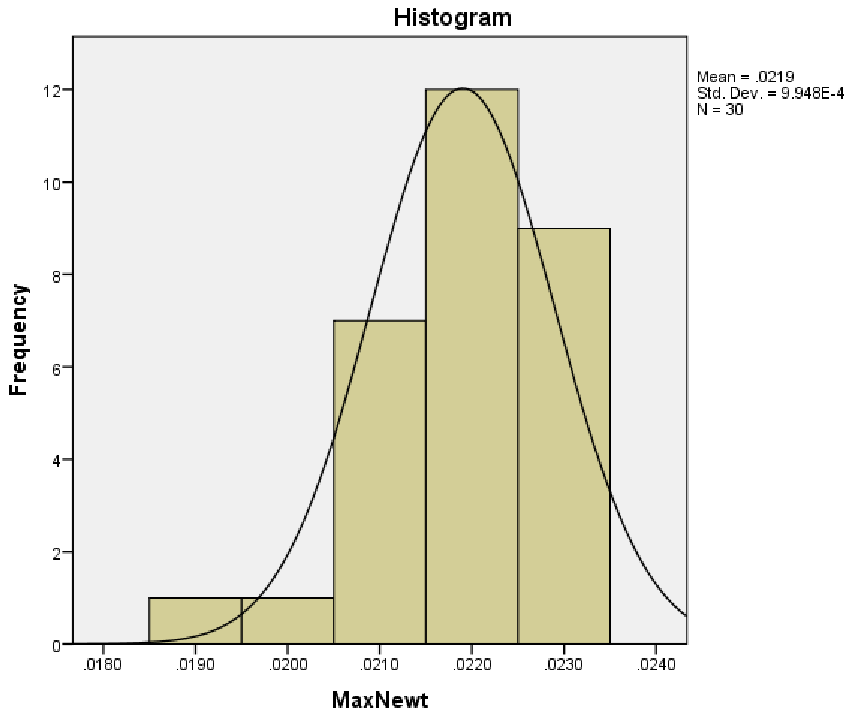

Figure 24: Project Study: Stone in Gel Histogram

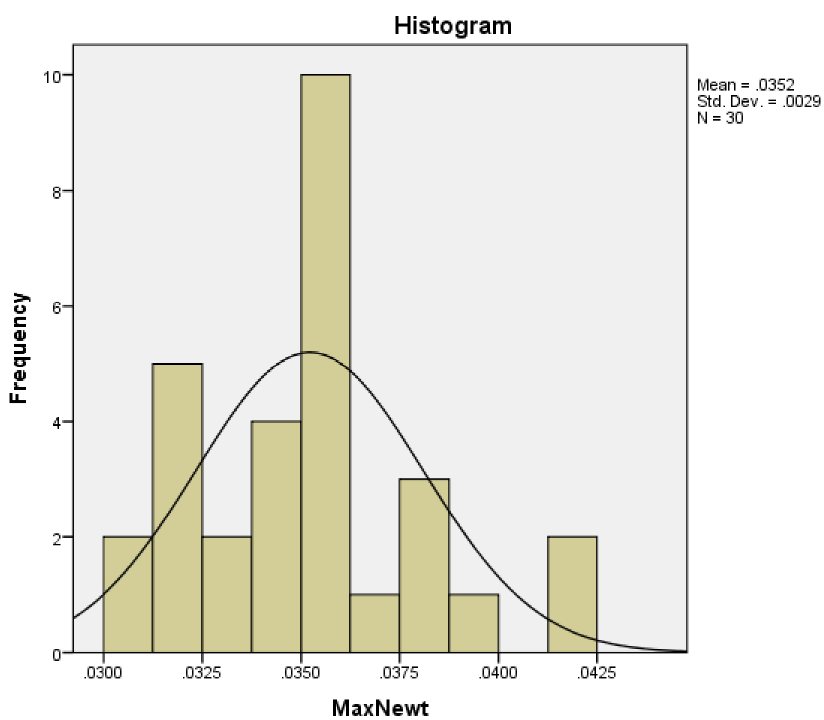

Figure 25: Project Study: Stone in Meat Histogram

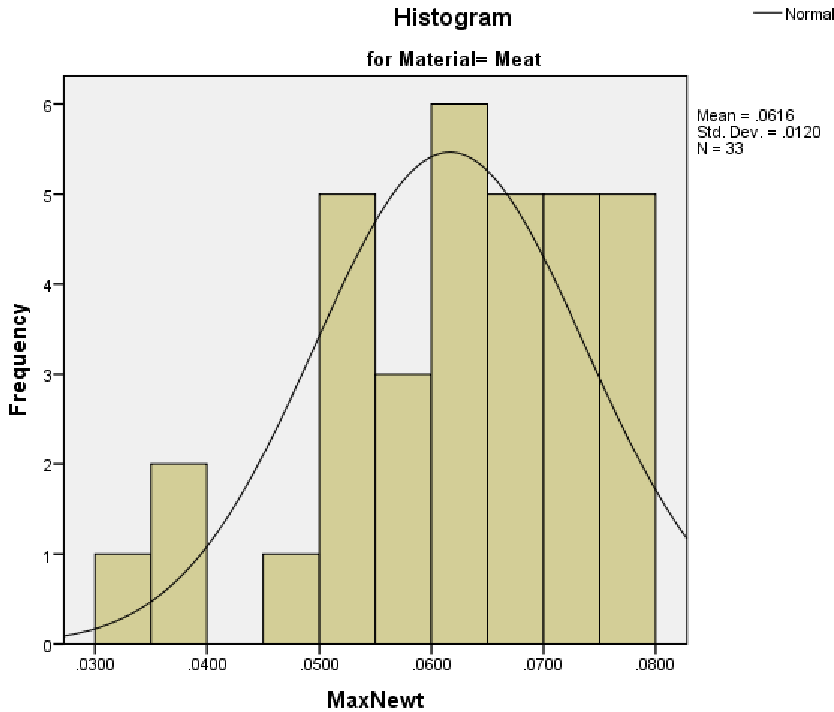

Figure 26: Project Study: Stone in Clay Histogram

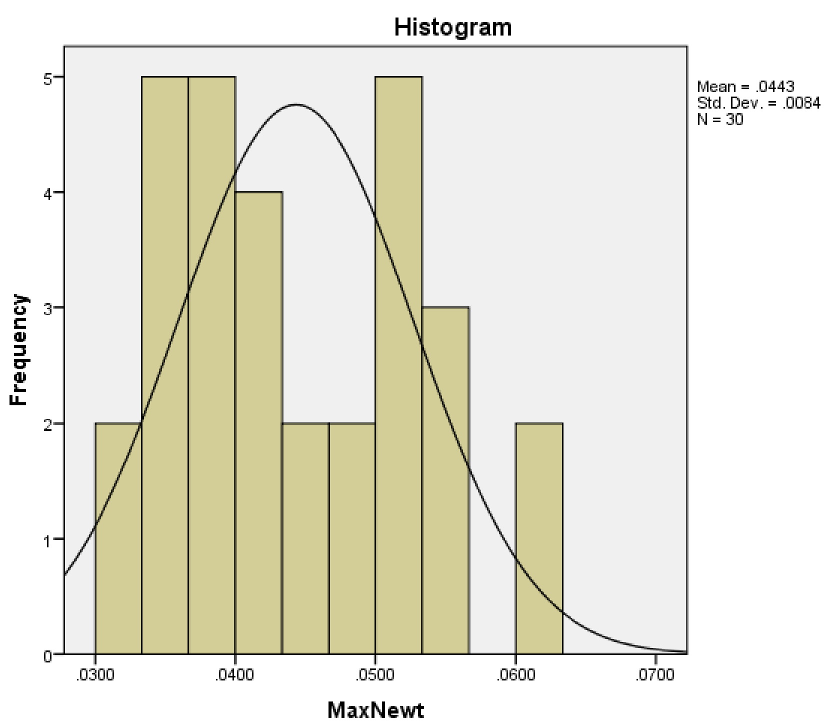

Figure 27: Project Study: Stone in 20 % Gel Histogram