NEW ANALYTICAL METHODS FOR COMPARING BONE FRACTURE ANGLES: A CONTROLLED STUDY OF HAMMERSTONE AND HYENA (*Crocuta crocuta*) LONG BONE BREAKAGE*

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Accurate interpretation of the cause and timing of bone breakage is essential for understanding the archaeological record. However, many variables potentially influencing break morphology have yet to be systematically explored. Focusing primarily on hammerstone breakage, we introduce new analytical methods for comparing fracture angles using the absolute values of the angle from 90°. We systematically control for intrinsic variables such as taxon, skeletal element, limb portion and skeletal age. We also compare experimental assemblages of femora broken by hammerstone and spotted hyena (*Crocuta crocuta*). We show that fracture angles are influenced by breakage plane, skeletal element and limb portion. While the latter two have been suggested before, this is the first time the differences have been quantified. We suggest that researchers stratify their assemblages by these variables if they are using fracture angles in analyses. At the assemblage level, hyenas created more oblique fracture angles on oblique breaks than did hammerstones.

**KEYWORDS:** BONE BREAKAGE, TAPHONOMY, EXPERIMENTAL ARCHAEOLOGY, CARNIVORE AND HUMAN BONE MODIFICATION

INTRODUCTION

Both humans and carnivores exploit marrow resources by cracking open the long bones of hunted or scavenged animals. Fossil and archaeological bones are often found broken, and if we can correctly infer the timing and cause of the breakage, we can interpret hominin meat and marrow exploitation strategies, hominin–carnivore interactions, agent(s) of bone accumulation and site formation issues better. Within archaeological contexts, it is generally assumed that the most common agents/effectors of post mortem fresh bone breakage are hominin tool users and carnivore teeth.

Although there have been many studies of bone breakage attempting to attribute breakage to particular causal agents and effectors, equiﬁnality remains a problem (Dart 1957; Brain 1978, 1981; Morlan 1980; Shipman 1981; Haynes 1983; Johnson 1985; Villa and Mahieu 1991; Lyman 1994; Outram 1998, 2001). This equiﬁnality concern is paralleled in many taphonomic issues, such as in cutmark (e.g., Thompson *et al.* 2015) and mortality curve studies (e.g., Stiner 1994). For bone breakage, signatures of human intentional breakage once included spiral fractures (Dart 1957, 1959; Bonnichsen 1989), but we now know that effectors other than twisting between the hands—such as carnivore teeth—can result in helical fractures, (e.g., Myers *et al.*
1980; Binford 1981; Brain 1981; Haynes 1983). Peeling, most commonly on ribs, may indicate human breakage (White 1992; Pickering et al. 2013), but can also be made by carnivores (Pickering et al. 2013; Arilla et al. 2014). Notches on breaks with broad arcuate shapes and high release angles also have been thought to differentiate hammerstone from carnivore breaks, but there is a large overlap in shape and angle (Capaldo and Blumenschine 1994; Soderberg and Tappen in prep.). Some types of breaks are often quite good for identifying carnivore damage, such as ‘crenulated’, or ‘ragged edge’, breaks and scooped articular ends (e.g., Maguire et al. 1980; Haynes 1983).

Common methods in breakage studies use categorical variables (Shipman 1981; Villa and Mahieu 1991; White 1992; Outram 1998, 2001). These systems are good for distinguishing fresh from very dry bone and post-fossilization breaks, but still cannot fully separate agents of fresh bone breakage. In practice, breakage agents are often identified using surface modifications such as percussion marks, tooth marks and trampling marks adjacent to the break, and not the break morphology per se (e.g., Galán et al. 2009). However, surface marks on excavated bones are often obscured by etching, exfoliation, abrasion or matrix, and many bone fragments, even if well preserved, can be devoid of surface marks.

Previous studies have suggested that carnivore tooth loading is slower and more akin to static loading, resulting in more right-angled fractures, while loading by hammerstones is more dynamic, or rapid, and leads to more oblique fracture angles (Bunn 1983; Capaldo and Blumenschine 1994; Alcántara-García et al. 2006). Alcántara-García et al. (2006) quantified fracture angles of experimentally broken bones and found that ‘static’ loading produced fracture angles between 80° and 110°, while ‘dynamic’ loading resulted in more obtuse (> 110°) or acute (< 80°) angles. The resulting angles from Alcántara-García et al.’s (2006) experiments seemed to be congruent with those observed in notches by Capaldo and Blumenschine (1994), where carnivore-made notches possessed release angles closer to 90° than those made by hammerstones. Pickering et al. (2005) and Domínguez-Rodrigo and Barba (2006) followed Alcántara-García et al.’s (2006) quantitative methods on long bone shaft fragments and compared their results to interpret bone breakage from Swartkrans and Olduvai, respectively.

More recently, however, de Juana and Domínguez-Rodrigo (2011) produced an experimental assemblage of equid bones broken by hammerstones and observed opposite trends to the bovid bones examined by Alcántara-García et al. (2006). Hammerstone breaks on equid bones generated fracture angle assemblages closer to 90° than did hammerstone broken bovid bones and were more similar to the carnivore broken sample. Thus, the complexities of characterizing bone breakage remain apparent, most probably due to the large number of variables influencing breakage. Bone is heterogeneous, anisotropic and varies in shape, size and thickness across taxa, elements and age.

It is within this epistemological framework that important questions emerge: Do fracture angle measurements really help identify the agents that break bone, or is there too much overlap in the angles? In this study, we explore differences between particular skeletal elements. If, for example, humeri and tibiae typically break at different angles, then assemblages with different abundances of these skeletal elements could be misinterpreted by researchers. Therefore, we conducted a controlled study of experimental breakage that controls for variables such as the skeletal elements themselves (e.g., humerus versus tibia). We focus our analysis on assemblage-level comparisons of fracture angles on long bone fragments measured with goniometers. Multiple researchers took repeated measurements to test for the precision and accuracy of our goniometer measurements. We controlled for several variables, including two marrow acquisition strategies, the skeletal age of the individual, the classification of the break plane, the size of the break and whether the
bone had been previously frozen. Our new method reveals which variables are necessary stratifications of breakage data for effective comparisons at the assemblage level.

METHODS

We conducted bone breakage experiments using two different methods: breaking bones with a hammerstone on an anvil and feeding bones to a spotted hyena. To keep body size constant, we used bones only from the carcasses of farm-raised, Rocky Mountain elk (Cervus canadensis nelsoni [~500–1000 lb; ~225–450 kg]), a size class 3 mammal (see Brain 1981; Bunn 1982). The experimental hammerstone sample constitutes 45 long bones with 729 measureable breaks on 264 fragments, and the hyena-broken sample constitutes 11 femora with 107 measureable breaks on 56 measured fragments (Table 1). For the hammerstone experiment, University of Minnesota students disarticulated and filleted long bones from two whole elk (= 15 long bones) using stone tools. We also obtained 30 defleshed individual long bones from the same elk farm. The individual long bones had been filleted by the farmer with metal implements and then frozen. Prior to the breakage experiment, all of the bones had been defleshed, but the periosteum remained.

Students broke the long bones along the diaphysis with the same hammerstone and stone anvil. The anvil, composed of a coarse-grained gabbro, weighs 11.2 kg, with a greatest dimension of 271 mm. The hammerstone is a finer-grained gabbro and weighs 1.3 kg, with a greatest dimension of 110 mm. We broke the bones from the whole individuals within 5 h of death, while the other 30 bones had been frozen for an unknown length of time, but thawed for over 24 h prior to breaking. The primary goal during the hammerstone breakage experiment was to access the marrow cavity as efficiently as possible. The most stable position of the bones on the anvil varied from element to element, although it usually proved to be the flattest surface of the long bone (e.g., either the medial or lateral shaft for metapodia).

The hyena-broken bone sample consists of 11 disarticulated, partially defleshed elk femora that were fed to an adult male spotted hyena (Crocuta crocuta) at the Milwaukee County Zoo. Like the hammerstone broken bones, these long bones were defleshed, but the periosteum remained. They had been previously frozen for an unknown length of time, but were thawed prior to being fed to the hyena. Due to concerns that the hyena would consume the entire bone, leaving

<table>
<thead>
<tr>
<th>Element</th>
<th>Number of bones</th>
<th>Percentage of bones</th>
<th>Number of fragments</th>
<th>Percentage of fragments</th>
<th>Number of breaks</th>
<th>Percentage of breaks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental hammerstone-broken assemblage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Femur</td>
<td>11</td>
<td>17.46</td>
<td>65</td>
<td>19.29</td>
<td>193</td>
<td>20.55</td>
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<tr>
<td>Humerus</td>
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<td>14.29</td>
<td>44</td>
<td>13.06</td>
<td>136</td>
<td>14.48</td>
</tr>
<tr>
<td>Tibia</td>
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<td>87</td>
<td>25.82</td>
<td>225</td>
<td>23.96</td>
</tr>
<tr>
<td>Radius</td>
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<td>14.29</td>
<td>45</td>
<td>13.35</td>
<td>110</td>
<td>11.71</td>
</tr>
<tr>
<td>Metacarpal</td>
<td>13</td>
<td>20.63</td>
<td>47</td>
<td>13.95</td>
<td>129</td>
<td>13.74</td>
</tr>
<tr>
<td>Metatarsal</td>
<td>10</td>
<td>15.87</td>
<td>49</td>
<td>14.54</td>
<td>146</td>
<td>15.55</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>63</td>
<td>100</td>
<td>337</td>
<td>100</td>
<td>939</td>
<td>100</td>
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<td><strong>Experimental hyena-broken assemblage</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Femur</td>
<td>11</td>
<td></td>
<td>56</td>
<td></td>
<td>107</td>
<td></td>
</tr>
</tbody>
</table>
no remnant fragments for these analyses, 10 bones were left with the hyena for less than 15 min. One bone was left with the hyena to see what might happen. The hyena almost completely destroyed the bone, but lost interest after 30 min, leaving only two measurable fragments. Although zoo studies may not reflect the degree of fragmentation produced in varying contexts in the wild (Pobiner 2007; Gidna et al. 2013; Sala et al. 2014), they do result in assemblage breakage by the effector of interest, since the masticatory apparatus and its function remains the same. Thus, zoo studies should produce an array of fracture angles of some use in approximating the population of possible carnivore-produced angles. Since we had fewer opportunities for hyena bone breakage, we kept the skeletal element constant (femur), but we are currently continuing these experiments with other skeletal elements.

After breakage and collection, we stored all of the bones in a freezer until processing. After thawing, we gently boiled the bones for several hours, after which we removed the remaining adhering tissue and tendons. Next, we simmered the bones for several more hours and, after a final brief cleaning and rinsing, air dried them on tables in the laboratory.

Fracture angle measurements

We examined the bone fragments and classified breaks as oblique, longitudinal or transverse according to fracture plane relative to the long axis of the bone (Fig. S1: see, e.g., Villa and Mahieu 1991; Pickering et al. 2005).

Oblique breaks can be helical or straight, but we follow the break plane classification in order to compare our results with previous quantitative work on long bone shaft fragments. In addition, we found that fragments containing small breaks were sometimes continuations of helical fractures; thus, using only breaks that were obviously helical would bias our sample towards larger breaks. We measured breaks >2 cm on fragments >4 cm. Our measurements expand the protocol set forth by Alcántara-García et al. (2006), who measured breaks >4 cm. We measured at the centre of the break using a goniometer held between the periosteal and break edge surfaces. Breaks can vary greatly in fracture angle along their course (e.g., Johnson 1985; Pickering et al. 2005) and our approach reduces this variation to a single point. By using the centre of the break, we aim to evaluate if this easily replicable and simple procedure reveals patterns at the assemblage level as suggested by previous researchers. We only measured cortical bone fractures on the shafts of long bones. The epiphyseal fragments measured had shaft portions with preserved cortical bone fractures.

We did not study fracture planes with notches (Capaldo and Blumenschine 1994; Soderberg and Tappen in prep.). Some angles were not physically measurable, such as fragments with >50% but <100% circumference remaining (see Bunn 1989) with highly acute fracture angles, because the goniometer could not touch both the periosteal and the break surfaces simultaneously (n = 27). We also did not measure hinge fractures because the topography of the fracture surface and angle vary widely at the same location. Each of the four observers measured each angle three times.

Measurements should be accurate and reliable and the process should be efficient and economical. It is important to control for intra- and inter-observer error to better understand the impact of measurement errors. The morphology of the bone fragment, as well as convexities and concavities of the break surface, can sometimes make measurements difficult to take, so we test for how this affects the resulting distributions at the assemblage level. Inter- and intra-observer tests reported below show that the measurement errors are not significant and help to alleviate concerns regarding goniometer inaccuracies and inconsistency.
Statistical tests

The further the angle is from 90°, the more the goniometer measurements may vary (Dibble and Bernard 1980). By recognizing that there is more variation in fracture angle measurements that are farther from 90°, especially on highly acute angles, we can more accurately interpret our results. With this in mind, fracture angle measurements were divided based on whether they were acute or obtuse. Permutation tests using $F$ and $T$ statistics are used for group- and pair-wise comparisons, respectively. Permutation tests are an effective way to compare different sets of data that do not conform to normal distributions. Essentially, permutation tests resample the observed data to construct distribution curves based on a certain test statistic. Each permutation creates a distribution curve and all the resulting curves are compared to one another (in this case, 5000 times). The null hypothesis of a permutation test states that all permutations result in the same distribution curve. If data sets are statistically different, then there is a low probability that the permutations will generate similar distribution curves more than 5% of the time.

For inter-observer tests, R.C. and three undergraduate students measured 146 breaks three times and all of the measurements are compared using permutation tests on both the acute and obtuse measurements. A larger sample based on R.C.’s measurements ($n=441$) is assessed for intra-observer error using the same methods. The null hypothesis for each test is that the groups represent samples from the same population, and there will be no statistical difference between groups ($p > 0.05$). Comparisons within the hammerstone assemblage and between hyena- and hammerstone-created assemblages are also separated into acute and obtuse angles. For significant group-wise permutation tests, Tukey honest significant difference (HSD) tests were subsequently run for comparisons on skeletal elements and limb portions (confidence level = 0.95). The null hypothesis is that each group represents a sample from the same population and $p$ is expected to be >0.05. We calculated effect size (Cohen’s $d$) for each pair-wise comparison within the hammerstone assemblage (Wolverton et al. 2016). We ran all statistical tests in R (v. 3.0.2). Graphs and tables were generated in Microsoft Excel.

RESULTS

Intra- and inter-observer error

We tested intra-observer error by examining differences among the three measurements by each researcher on each fracture angle for oblique breakage planes. For the intra-observer error of the larger sample ($n=441$), the permutation tests show no statistical difference between any of the sets of measurements regardless of angle type (acute, $p=0.590$; obtuse, $p=0.877$), suggesting that measuring each angle more than once is redundant and unnecessary in order to attain consistent results at the assemblage level.

For inter-observer error, the permutation tests between observers resulted in no statistical difference between any of the researchers’ data regardless of angle type (acute, $p=0.943$; obtuse, $p=0.977$). Therefore, due to statistically similar results and a larger sample size, only R.C.’s measurements are used for the following assemblage comparisons.

Fracture angle

Fracture angles were tested to see if there were differences in how far acute and obtuse angles averaged from 90° using the absolute values. We then ran pair-wise permutation tests between acute and obtuse fracture angle on oblique and longitudinal breaks. We found statistically
significant differences between each set (oblique, \(p=0.0004\); longitudinal, \(p=0.00\)), and therefore examine acute and obtuse angles separately.

**Fracture plane**

The hammerstone experiment resulted in 441 oblique, 265 longitudinal and 23 transverse fracture planes \(>2\) cm long (Table 2). Alcántara-García *et al.* (2006) found that transverse breaks were rare and the fracture angles had a high degree of overlap between ‘dynamic’ and ‘static’ forces. In agreement with Alcántara-García *et al.* (2006) and Pickering *et al.* (2005), we focused our analysis on oblique and longitudinal breakage planes. The distribution of the fracture angles parsed by breakage plane and their absolute distances from \(90^\circ\) are shown in Figure 1 (Table 2).

A permutation test comparing means of fracture angles for oblique and longitudinal break planes shows a significant difference between acute and obtuse angles (acute, \(p=0\); obtuse, \(p=0\)), which does not support the null hypothesis (Table 2). This supports the notion that different break plane orientations yield different distances from \(90^\circ\) at the assemblage level; the longitudinal breaks are closer to \(90^\circ\) than the oblique breaks. Therefore, as demonstrated by Alcántara-García *et al.* (2006) and Pickering *et al.* (2005), it is necessary to analyse fracture angles according to break plane. The following five sections will look at oblique breakage planes only.

**Marrow acquisition strategy**

We divided the assemblage by two different marrow acquisition strategies that we employed during the experimental hammerstone breakage. In the first year of the experiment, the goal was simply to access the marrow cavity in as few impacts as possible, which limited physical exertion during breakage, but could increase subsequent marrow extraction time. In subsequent experiments, a slightly different method was employed, similar to that of Bunn (1989), where the bone was struck at two or more locations in order to access the entire length of the marrow cavity more effectively, but still with as few impacts as possible. The latter method has more exertion up front, but less work to fully extract the marrow. The permutation tests using the \(T\)-statistic resulted in no statistically significant difference between the two methods in obtuse and acute angles (Table 2). As a result, both methods are included in the subsequent analyses of fracture angles.

**Bone freshness**

Comparing fracture angle assemblages of the fresh and the once-frozen bones informs us if prior freezing had confounding effects on the breakage dynamics (Outram 1998, 2001; Karr and Outram 2012a,b). The permutation tests between the fracture angles of bones broken while fresh and those once frozen and then thawed before breakage resulted in no significant differences, supporting the null hypothesis (Table 2). Since prior freezing of bones resulted in no differences in angles, we use both fresh and once-frozen bone in our subsequent analyses.

**Long bone shaft fragments versus epiphyseal fragments**

Epiphyseal fragments have epiphyseal ends but also retain part of the diaphysis where break angles are measured. They are less abundant, but they are typically more identifiable than shaft fragments in archaeological assemblages. Including the epiphyseal fragments in analyses can increase the sample size of identifiable specimens.
Table 2  The results of Cohen’s $d$ and pair-wise permutation tests for different variables in the hammerstone assemblage. The first column represents the first variable of the pair-wise test and the second column is the second variable. The sample sizes are in parentheses. Long, longitudinal breaks; HS 1, bones struck in one location during breakage; HS 2, bones struck in multiple locations during breakage; LBSF, long bone shaft fragments; LBEF, long bone epiphyseal fragments; $<4$ cm, break lengths between 2 and 4 cm; $>4$ cm, break lengths longer than 4 cm; HS-Obl, oblique breaks from the femora of the hammerstone-created assemblage; Hyena-Obl, oblique breaks from the hyena-created assemblage; HS-Long, longitudinal breaks from the femora of the hammerstone-created assemblage; Hyena-Long, longitudinal breaks from the hyena-created assemblage.

<table>
<thead>
<tr>
<th>Var1 (n)</th>
<th>Var2 (n)</th>
<th>Acute</th>
<th>Oblique</th>
<th>ΣVar1</th>
<th>ΣVar2</th>
<th>Cohen’s d*</th>
<th>Permutation test results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oblique (556)</td>
<td>Long (359)</td>
<td>68.17</td>
<td>74.19</td>
<td>114.5</td>
<td>109.16</td>
<td>182.67</td>
<td>183.35</td>
</tr>
<tr>
<td>HS 1 (314)</td>
<td>HS 2 (242)</td>
<td>69.2</td>
<td>67.55</td>
<td>114.5</td>
<td>114.5</td>
<td>183.7</td>
<td>182.05</td>
</tr>
<tr>
<td>Frozen (446)</td>
<td>Fresh (110)</td>
<td>68.19</td>
<td>68.09</td>
<td>114.43</td>
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<td>182.62</td>
<td>182.89</td>
</tr>
<tr>
<td>LBSF (382)</td>
<td>LBEF (174)</td>
<td>65.99</td>
<td>74.62</td>
<td>112.53</td>
<td>117.99</td>
<td>178.52</td>
<td>192.61</td>
</tr>
<tr>
<td>Fused (330)</td>
<td>Unfused (226)</td>
<td>68.98</td>
<td>66.87</td>
<td>113.62</td>
<td>115.7</td>
<td>182.6</td>
<td>182.57</td>
</tr>
<tr>
<td>&lt;4 cm (313)</td>
<td>&gt;4 cm (243)</td>
<td>68.02</td>
<td>69.46</td>
<td>113.64</td>
<td>115.23</td>
<td>181.66</td>
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<tr>
<td>HS-Obl (116)</td>
<td>Hyena-Obl (76)</td>
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</tr>
<tr>
<td>HS-Long (65)</td>
<td>Hyena-Long (31)</td>
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<td>71.08</td>
<td>109.35</td>
<td>115.44</td>
<td>175.5</td>
<td>186.52</td>
</tr>
</tbody>
</table>

*Estimates of Cohen’s $d$. Unqualified results represent negligible size effects.
†Small size effects.
‡Medium size effects.
The permutation tests between shaft and epiphyseal fragments resulted in significant differences between the two assemblages for both acute and obtuse angles; thus we reject the null hypothesis (Table 2). These differences result from potential biases in both the measurements.

Figure 1  Histograms of the frequencies of fracture angle measurements on oblique and longitudinal breaks for both (a) raw angle measurements and (b) the angle measurement distances from 90°.

The permutation tests between shaft and epiphyseal fragments resulted in significant differences between the two assemblages for both acute and obtuse angles; thus we reject the null hypothesis (Table 2). These differences result from potential biases in both the measurements.
and fracture dynamics of each fragment type. Due to the paired nature of angles, we expect the sum to add up to 180°. As mentioned previously, measurement biases exist for highly acute angles, but these biases seem to differentially affect the fragment types. Due to the shape of the epiphyseal fragments, highly acute angles are rarely measurable, which is reflected in the sum of acute and obtuse angles (192.61°). For obtuse angles, fracture dynamics affect the size of measurable breaks on shaft fragments. These obtuse angles are under-represented, which is reflected in the sum (178.52°). We discuss these biases in more detail below, but further analyses of fracture dynamics need to be undertaken.

Fused versus unfused

Some of the bones used in our study have unfused epiphyses, including those from 18-month-old females and individual bones that we estimate to be approximately the same age based on size and state of fusion. Skeletal structures change in size, shape and mineralization during ontogeny, which can potentially change fracture dynamics. However, the permutation tests of the unfused and fused bones resulted in no significant difference, supporting the null hypothesis that both the skeletally adult and juvenile bones produce similar fracture angle patterns (Table 2). At least for long bones of one and a half year olds, the fusion state does not affect the breakage angles in any significant way.

Fracture length

We observed that smaller breaks (2–4 cm) shared many characteristic properties with breaks larger than 4 cm, so we include breaks with smaller dimensions than did Alcántara-García et al. (2006). Our sample includes all measurable breaks >2 cm on fragments >4 cm. We found no statistical difference between the two size classes using pair-wise permutation tests, indicating that fracture angles for each size class had very similar distributions (Table 2). Therefore, all breaks larger than 2 cm are used in the following comparisons.

Skeletal element

Perhaps the most informative comparison is by skeletal element. Table S1 shows the sample size, mean and the absolute value of fracture angles from 90° for acute and obtuse angles on both longitudinal and oblique break planes for each skeletal element and limb portion. Oblique breaks for each skeletal element were compared to all other oblique breaks using group-wise permutation tests using the F-statistic to determine whether there are differences in fracture angle distributions among the skeletal elements. There are significant differences between skeletal elements for both acute and obtuse fracture angles (p = 0.00 for both tests).

Therefore, we ran Tukey HSD tests for each pair-wise comparison to locate the differences. There are significant differences between several samples (Table S2). The histograms (Fig. 2) show that the highest proportion of near right-angled breaks belongs to the metapodia, followed by the tibia and radius. The femur and humerus have generally more oblique fracture angles.

It is sometimes difficult to determine the exact skeletal element of a shaft fragment, but one can still identify fragments to limb portion—upper (humerus, femur), middle (radius, tibia) or lower (metacarpal, metatarsal) limb—based on the morphology (Pickering et al. 2006). Permutation tests on fracture angles according to limb portion were significant for both acute and obtuse angles (p = 0.00 for both tests), so further Tukey HSD tests were run. Based on the
Tukey HSD test results, the fracture angles of upper limb bones (femur and humerus) are significantly different from those of the middle and lower limb (Table S3). The histogram shows more right-angled distributions for the middle and lower limb bones, and a more oblique distribution for upper limb bones, which corroborates the Tukey HSD test results (Fig. 3).

We also tested longitudinal break plane fracture angles for each skeletal element to see if the pattern persisted. Permutation tests showed significant differences among skeletal elements for longitudinal fractures for both acute and obtuse angles (acute, $p = 0.00$; obtuse, $p = 0.0018$). Since

Figure 2  Histograms of oblique break fracture angle distances from 90° for each skeletal element and limb portions: (a) femur; (b) humerus; (c) tibia; (d) radius; (e) metatarsal; (f) metacarpal. Acute fracture angles are represented by shaded bars while obtuse fractures angles are represented by hollow bars.
Figure 3  Histograms of oblique break fracture angle distances from 90° for (a) upper, (b) middle and (c) lower limb portions. Acute fracture angles are represented by shaded bars while obtuse fractures angles are represented by hollow bars.
the permutation tests returned significant $p$-values, Tukey HSD tests were run. Some pair-wise comparisons resulted in significant differences (Table S2).

Comparisons on limb portions for the longitudinal breaks also show significant differences in the oblique breaks for limb portions, though only for acute angles. The permutation tests between fracture angles by limb portions resulted in a significant difference for acute angles ($p = 0.00$), but not of obtuse angles ($p = 0.3636$). When looking at the pair-wise comparisons on acute angles using the Tukey HSD tests, the upper limb bones are significantly different from the middle and lower limb bones. However, there is no significant difference between lower limb bones and the middle bones (Table S3). This suggests that, although longitudinal breaks generally have fracture angles closer to 90° than oblique breaks, upper limb bones still have more oblique fracture angles than middle and lower limb bones.

**Hammerstone and carnivore fracture angle**

The hyena breakage experiment is based on a sample made up only of femora, and thus should be considered preliminary. Although we have only one element, we have a similarly sized sample of measured breaks on femora for the hammerstone and hyena samples (Fig. 4 and Table 2). The pair-wise permutation tests between the oblique breaks of the two groups was not significant for the obtuse angles ($p = 0.131$), supporting the null hypothesis that both hyena and hammerstone breakage assemblages yield similar fracture angle means. Acute angles, however, were significantly different ($p = 0.0288$), rejecting the null hypothesis.

Permutation tests comparing fracture angles on longitudinal breaks between these two groups resulted in no significant difference for both acute and obtuse angles (acute, $p = 0.253$; obtuse, $p = 0.083$). The means of each group are more similar, again affirming that longitudinal break fracture angles are probably less informative than those of oblique breaks (Table 2).

![Figure 4](image)

**Figure 4** A histogram of oblique break fracture angle distances from 90° for femora broken by hammerstones and hyenas. Sample sizes are in parentheses.
Our methodology explores bone fracture angles, one of many aspects of bone breakage that can be studied. The purpose is to scrutinize this aspect and variables that may influence them. Our work expands on the few explorations of this primary variable first quantified by Alcántara-García et al. (2006).

We found that smaller breaks (2–4 cm in length) are probably as informative as larger breaks (> 4 cm) and can be included in analyses. As shown in Table 2, over half of our oblique break sample comes from breaks that are 2–4 cm, and there is no statistical difference between fracture angles on breaks less than 4 cm and those greater than 4 cm. Our observations of these breaks disagree with Alcántara-García et al. (2006) in the sense that many of these small breaks do represent entire, unconstrained break surfaces, especially for oblique and transversely oriented breaks. Including break surfaces larger than 4 cm could potentially bias samples towards longitudinal breaks, and may limit the number of usable breaks in size class 1–2 animals because their long bone shaft widths are smaller. As a consequence, oblique breaks will be under-represented, which is even true for our results with size class 3 elk (Table 2).

In addition to the inclusion of shorter break surfaces, we include fragments that retain an epiphysis in our analysis to increase sample size because there is a very high success rate for identifying fragments retaining whole or partial epiphyses to element, and taxon. Their inclusion becomes extremely important, especially in light of the differences found in skeletal element and limb portions.

The completeness of these specimens, however, is also a constraining factor on data collection. For acute angles, fracture angle measurements on breaks connected to epiphyseal fragments were closer to 90°. This is probably due to the difficulty in taking goniometer measurements on these fragments, since the higher degree of circumference remaining leaves more obstacles for measurement; thus these breaks were not measured. One would expect that acute and obtuse averages to add up to 180°, since each obtuse angle would have a corresponding acute angle. However, there is bias—the sum of the acute and obtuse angles for epiphyseal fragments is 192.61°; the average for acute angles is much higher than expected, given the measured obtuse angle values.

When looking at the sum of the acute and obtuse angles for each variable (Table 2), all but one variable (long bone shaft fragments) have sums higher than 180°. Again, this demonstrates a measurement bias against highly acute angles, probably resulting from the morphology of the bone fragments and the constraints of the goniometer itself, and/or possibly the way in which bone shatters and releases small fragments near the impact point. This bias would result in asymmetrical distance estimates from 90°.

Our results support the notion that bones break differently based on their overall shape and cortical bone thickness and density, which tend to increase as one moves distally down the limb. Therefore, it is important to compare bones from the same limb portions (upper, middle, lower limb), if not the specific element themselves. This can be problematic for archaeological assemblages where the long bone shaft fragments are not easily identifiable to element, but if they are identified to limb portion, the comparisons can be made. This limb portion difference relates back to our initial question regarding how intrinsic factors of the bones themselves affect breakage morphology.

Bone is hierarchically structured; it can be dense cortical bone, which can be primary lamellar bone or have various degrees of Haversian remodelling, or it can be trabecular, with struts occurring at various thicknesses and angles. At a finer scale, bone is composed of mineral crystals that are arranged along collagen fibres that run parallel to the longitudinal axis of long bones. The
organization of collagen and mineral crystals is a critical factor affecting the strength and fracture of bone (Tappen 1969; Ji and Gao 2004; Burr and Allen 2014). For these reasons bone is anisotropic and viscoelastic. Viscoelasticity of protein in bone assists in the dissipation of fracture energy (Ji and Gao 2004). Bones are stronger under compressive strain than tensile or shear strain, and cracks and breakage may follow structures at various levels (Burr and Allen 2014; Symes et al. 2014). These structural properties of bone can provide predictive parameters for assessing how bone will fracture.

There is considerable morphological variability between skeletal elements as well. The size of the element and the thickness of the cortical bone vary allometrically across size classes. The stressed volume effect asserts that large volumes fail faster than smaller volumes (Taylor and Kuiper 2001), so there is an interplay between mass and volume and the effect on stress resistance. Additionally, there is a taxon-specific aspect of variation in bone thickness, shape, and quantity of marrow. As animals age, bone fusion states change and mineralization accelerates, but this appears to not affect fracture angles in our study, as we found that unfused bones of near adult-sized animals did not break at statistically different angles than the adult fused bones. These intrinsic factors affect how fresh bone will respond to localized force and how breaks will propagate.

There are also extrinsic factors that need to be considered, such as the source of the force and how it is exerted on the bone. There are several agents that can create the force necessary to break a bone, including hominins, carnivores, trampling by animals and so on. The effectors employed by agents (e.g., stone tool, dental arcade or hoof) vary in size and shape. A jagged-edged chopper will make contact with the bone differently than a rounded hammerstone. The same can be said about a premolar versus a molar, the typical bite points for bone cracking hyenas versus bone crushing canids, respectively (Werdelin 1989; Tseng et al. 2011). In addition, carnivore teeth are smaller than hammerstones and arranged in a linear fashion. Hammerstones and anvils also vary in size.

The magnitude and the angle of force can also affect how bone will break, whether oblique or perpendicular to the main axis of the bone. The location of the force, whether midshaft or closer to the proximal or distal end, will impact bone breakage patterns, though not significantly in our analysis of fracture angles. The rate of loading varies among agents. A hammerstone strikes the bone quickly, whereas a carnivore gnaws or bites down with supposedly a slower, more continuous pressure (referred to in some of the literature as dynamic or static, respectively; see, e.g., Bunn 1989; Capaldo and Blumenschine 1994). The number of times the bone is struck or bitten will also vary by individual agent and their situation.

The state of the bone at the time of breakage influences outcomes. If the bone is broken shortly after death, the break takes on characteristics of green bone fractures. As collagen decays and the bone and the mineralization process advances, the breaks become dry breaks. However, there are various stages that are not addressed by the dichotomy of ‘green’ and ‘dry’ break categories. After death, as the bone loses water and the organic material decays, the viscoelastic properties are lost. Drying occurs over a continuum of time, resulting in a gradual transition from fresh to dry. Breaks become more often jagged, nearer to right angles and have fewer curved fracture outlines over a duration of months as they dry (Wieberg and Wescott 2008; Symes et al. 2014). Our experimental bone fracture angles were indistinguishable if the bone had been previously frozen and then thawed, so to detect this experimental history one would need to use other variables (Karr and Outram 2012a,b).

Our results indicate that some of bone’s intrinsic variables quantifiably affect fracture angles. Specifically, the shape and size of different limb bones, along with cortical bone thickness,
appear to affect the resulting fracture angles at the assemblage level. However, fracture angles resulted in statistically significant differences in only one comparison between hammerstone broken and hyena broken bones (acute fracture angles on oblique breaks).

CONCLUSIONS

We have provided a new method for analysing bone fracture angles using raw angles and the fracture angle distance from 90° at the level of the bone assemblage. We have shown that, in many cases, fracture angles are strongly affected by the skeletal element or limb portion from which the bone fragment originates. In some areas, our results agree with what other researchers have already postulated; that is, oblique breaks should be compared to oblique breaks (Pickering et al. 2005; Alcántara-García et al. 2006; de Juana and Domínguez-Rodrigo 2011). However, contrary to the results from the breakage experiment from Alcántara-García et al. (2006), our results indicate that at the assemblage level for the femur, hyena broken assemblages have fracture angles very similar to those made by hammerstone, and if there are differences, the hyena assemblages tend to have fracture angles further from 90° than those made by hammerstone (Fig. 4). Possibly some of our differences in results may be due to different taxa used in the experiments, because Alcántara-García et al. (2006) used sheep, goat, pig and cow bones. This may suggest that the idea that hammerstone breakage creates more oblique fracture angles than carnivores is incorrect. Expanded experiments for all size classes are needed. In any case, the application of inferential statistics on our fracture angle measurements has revealed several interesting points:

1. Several variables do not impact fracture angles; therefore sampling does not need to be stratified based on these variables. This allows the inclusion of a broad sample of measurable fracture angles and mitigates potential sampling biases:
   - Within the hammerstone sample, it did not matter whether the bones were struck in one location at the centre of the shaft or at two or more locations along the shaft.
   - The changes in the skeletal structure during the late stages of ontogeny have no bearing on fracture angles, and adults and sub-adults can be analysed together (near 1.5 years and older for elk).
   - The inclusion of smaller fracture planes avoids bias due to exclusion of small taxa. Fracture length, whether >4 cm or <4 cm, did not show significant differences in fracture angle.

2. Break plane, skeletal element and skeletal region do affect fracture angles and thus samples should be stratified according to these variables:
   - The inclusion of epiphyseal fragments broadens the sample and allows for the analysis of specimens that are more likely to be identified to taxon. Measurement bias pertaining to goniometer methodology probably plays a role in the differences in acute-angled fractures.
   - Fracture angles from oblique breakage planes are probably more informative for comparisons than are those of transverse and longitudinal breaks.
   - Our results suggest that bones break differently based on their overall shape and cortical bone thickness, and density intrinsic to different skeletal elements. Metapodia, tibiae and radii are characterized by more right-angled fracture than humeri and femora. While this has been suggested before, this is the first time the differences have been quantified.
   - It may be best to compare bones based on whether they are from the upper, middle or lower limb. This is helpful considering that long bone shaft fragments can often only be identified to that level.

Expanding the analysis of hyena breakage to include all skeletal elements should inform further on the usefulness of fracture angles for distinguishing between hyena and hammerstone.
breaks. There was one statistically significant difference found among the fracture angles for the hyena versus hammerstone samples, and mixed results encumber the predictive power of such tests. In most cases (three out of four assemblages), hyena fracture angles on oblique breaks are farther from 90° (more acute or obtuse) than the hammerstone-created fracture angles. Our limited sample of skeletal elements broken by hyenas supports the idea that assemblages created by hominins and hyenas can be distinguished based on fracture angle, but a broadening of experiments and analyses is necessary to understand the extent of the variation.

Ultimately, a combination of fracture angle, morphology, location and surface modifications will be the best indicators for determining break cause, and teasing apart the influences on fracture angles is an important step in this direction. Identifying variables that influence breakage dynamics is paramount and this must be accomplished prior to confidently assessing the breakage agents. Our work indicates that when fracture angles are studied in archaeological contexts, researchers will have to identify bone fragments to skeletal element or at least limb portion.

ACKNOWLEDGEMENTS

This work was partially funded by the Department of Anthropology at the University of Minnesota and a National Science Foundation Grant (#1019408) to Martha Tappen. We are grateful to all the students who participated in this project, especially Cassie Clifford, Joel Cramblit, Sommer Osborn, Suzy Reece, Laura Scheid and Jason Zowin. Thanks go to Josh Feinberg for identifying the stone of our anvil and hammerstone. We thank Tim Wild, the numerous zookeepers and Scruffy from the Milwaukee County Zoo. We also thank Scott Salonek and the Elk Marketing Council for providing the whole elk and individual long bone specimens. This work could not have been undertaken without the efforts of John Soderberg and Keith Manthie; and benefitted from discussions with Gil Tostevin and Kieran McNulty. Special thanks are offered to Sanford Weisberg and Baolin Wu for statistics consultation. We are grateful for helpful revisions and suggestions from Aaron Armstrong, Gilliane Monnier, Katherine Erdman and two anonymous reviewers.

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New analytical methods for comparing bone fracture angles


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**SUPPORTING INFORMATION**

Additional Supporting Information may be found in the online version of this paper at the publisher’s web-site:

Table S1: Sample sizes (*n*), means (*x̄*), and absolute value of the distance from 90° (abs(−90)) of acute and obtuse fracture angles on oblique and longitudinal breaks for each skeletal element and limb portion.

Table S2: Results from Tukey HSD tests on the acute and obtuse fracture angles for oblique and longitudinal breaks on skeletal elements. The *p*-values are listed with those in bold being significant. Grayed out cells indicate the results for acute angles, and white cells are for obtuse angles.

Table S3: Results from Tukey HSD tests on the acute and obtuse fracture angles for oblique and longitudinal breaks on limb portions. The *p*-values are listed with those in bold being significant. Grayed out cells indicate the results for acute angles, and white cells are for obtuse angles. Numbers in italics represent Tukey HSD tests on non-significant permutation tests.

Figure S1: A labeled fragment illustrating the classifications of breakage planes relative to the long axis of the bone: A-Oblique; B-Transverse; C-Longitudinal. Photo taken by Sam Porter.
Figure S1: A labeled fragment illustrating the classifications of breakage planes relative to the long axis of the bone: A-Oblique; B-Transverse; C-Longitudinal. Photo taken by Sam Porter.
Table S1: Sample sizes ($n$), means ($\bar{x}$), and absolute value of the distance from 90° (abs(-90)) of acute and obtuse fracture angles on oblique and longitudinal breaks for each skeletal element and limb portion.

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Table S2: Results from Tukey HSD tests on the acute and obtuse fracture angles for oblique and longitudinal breaks on skeletal elements. The \( p \)-values are listed with those in bold being significant. Grayed out cells indicate the results for acute angles, and white cells are for obtuse angles.

<table>
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