Angling in on bone breakage: A controlled study of hammerstone and hyena (*Crocuta crocuta*) long bone breakage

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Abstract

Bone breakage forms important evidence for interpreting taphonomic history and hominin behaviors at paleoanthropological sites. Bone breakage analysis usually can determine the timing of breakage (as fresh, dry, or fossil bone) and aims at identifying agents of breakage (e.g. hominins, carnivores, trampling, compaction in sediments). Crenulated breaks associated with tooth pits on spongy bone/ long bone epiphyses indicate carnivore breakage, but identifying causes of breakage on long bone shafts is more problematic if tooth or hammerstone pits are not preserved or are covered by matrix. Studies of notches and breaks on shaft fragments have suggested that carnivore tooth loading results in more perpendicular break angles, while hammerstone dynamic loading leads to more oblique fracture angles (Capaldo and Blumenschine, 1994, Alcántara-Garcia et al. 2006), but variation due to variables such as size class, shapes and thickness of skeletal elements, location of impact, degree of force applied, and even taxonomic group (de Juana, S. and Domínguez-Rodrigo, M. 2011) means that large scale controlled studies are required.

We present experiments of hammerstone and carnivore broken long bones controlling for body size and taxon by using only *Cervus canadensis* long bones. We chose North American elk because it represents a size class commonly found at Pleistocene sites. The breaks were classified as oblique, longitudinal, or transverse after (Villa and Mahieu,1991 and Pickering et al. 2005) and angles measured following the protocol of (Alcántara-Garcia et al. 2006). The hammerstone sample consists of 45 long bones, 263 measured fragments, and 765 measureable breaks; the hyena broken sample consists of 11 femora, 60 fragments, and 111 breaks. We compare angles measured using goniometers between skeletal elements and to previously published data. Intra- and inter-observer error estimates are made and measurements are compared to 3D models in Geomagic.

Research Questions

- **What are the distributions of fracture angles from long bones broken with hammerstones?**
- **Are the measurements made with a goniometer accurate and replicable?**
- **How much does the skeletal element itself (e.g. femur versus metapodial) determine the fracture angle?**
- **Are the experimental fracture angle distributions different from those broken by spotted hyenas?**
- **Does our study replicate the results of previous studies?**

Methods

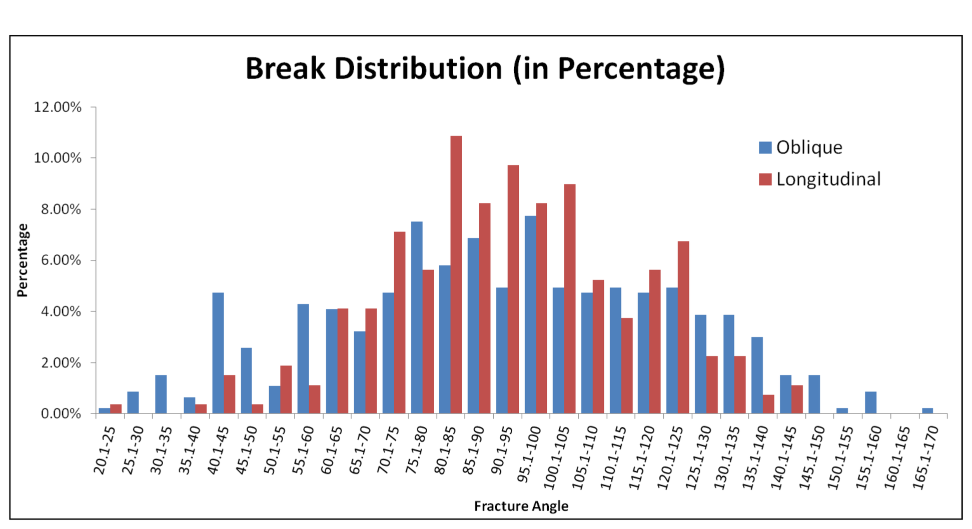
In these experiments, **we controlled for body size by using only bones of American elk**, *Cervus canadensis,* a size class 3 mammal (450-1100 lbs). Measurements were taken by placing the goniometer on the periosteal surface and the bar on the fracture edge.

Long bones were broken along the diaphysis with a hammer stone on a stone anvil. Bones were placed in the position that seemed most stable and where they could most easily be broken. Eleven disarticulated, partly defleshed elk (*Cervus canadensis*) femora were fed to an adult male spotted hyena (*Crocuta crocuta*) at Milwaukee Public Zoo. All but one bone were left with the hyena for less than 15 minutes after which the fragments were collected to be cleaned and measured. One bone was left with the hyena until it lost interest (less than 30 minutes). In both samples the bones had been filleted of their meat but periosteum remained. After breakage, the bones were gently boiled in water with non-alkaline laundry detergent to clean them of adhering tissue.

Age was determined by epiphyseal fusion for all unknown specimens, with unfused and fusing bones being assigned to juveniles, and completely fused bones assigned to adults. 15 juvenile bones from known individuals were broken fresh, within 5 hours of death, and 30 bones from various individuals were frozen for an unknown length of time but left to thaw for over 24 hours prior to breaking.

Measurement Parameters

- Classified each measurable break on the bone fragments as oblique, longitudinal, or transverse, after Villa and Mahieu, 1991 and Pickering et al., 2005
- Followed protocol of Alcantara-Garcia et al., 2006:
  - Measured only fragments >4 cm in length.
  - Measured fracture angles on breaks >2 cm in length without interruptions, such as notches or cracks
  - Analysis focused on oblique breaks
- Additional parameters
  - Fractures deemed immeasurable if goniometer did not touch both cortical and break surfaces (i.e. hinge fractures, acute angles on fragments with >50% circumference)
  - Measured 3 times at the midpoint of the break
  - Calculated angle distances from 90 degrees
    - More helpful for comparing acute to obtuse angle measurements



The Sample

The experimental hammerstone sample consists of 45 elk long bones of various ages, including 15 bones from two individuals of known ages (18 months) and the remaining 30 of various ages.

Total Experimental Hammerstone Breakage Assemblage

Element	*n* Bones	% Bones	*n* Measured Frags	% Frags	*n* Measured Breaks	% Breaks
Femur	11	24.44%	62	23.57%	194	25.36%
Humerus	9	20.00%	48	18.25%	154	20.13%
Tibia	11	24.44%	89	33.84%	236	30.85%
Radius	9	20.00%	42	15.97%	111	14.51%
MTC	2	4.44%	7	2.66%	20	2.61%
MTT	3	6.67%	15	5.70%	50	6.54%
Total	45	100%	263	100%	765	100%

Experimental Hyena Breakage Assemblage

Element	*n* Bones	*n* Measured Frags	*n* Measured Breaks
Femur	11	60	111

Inter and Intra-Observer Error

We tested for accuracy and reliability of goniometer measurements by measuring each break three times and taking the average for each of three researchers. Using Reed Coil's measurements as the expected measures, we tested for inter- and intra-observer error (modeled after Dibble and Bernard, 1980):

- Ran F-tests to determine if each group of measurements had equal variance.
- Ran T-tests to test the null hypothesis that there is no statistical difference between any of the researcher's results.
- No significant differences between observers or single person's observations: supports the null hypothesis
- Shows that goniometer measurements are repeatable and perhaps measuring angles more than once is redundant and unnecessary

Intra-Observer Error for Oblique Breaks (466)

	Observation 1	Observation 2	Observation 3
Observation 1	t-test	0.85745105	0.60302411
Observation 2	0.85347527		0.73351468
Observation 3	0.72554944	0.86723874	F-test

Inter-Observer Error: Oblique Breaks (n=157)

	Observer 1	Observer 2	Observer 3	Observer 4
Observer 1	t-test	**1.28104E-05**	0.578234295	0.283156698
Observer 2	0.943794582		**9.56453E-07**	**6.79257E-08**
Observer 3	0.476370347	0.519275504		0.604601727
Observer 4	0.51944081	0.557154897	0.932973417	F-test

- Calculated percent error to estimate the consistency of measurements between researchers, resulting in negligible differences between observers and the expected mean (Reed Coil's observations)
- Computed percent error based on following formula:

$$\%\ \text{Error} = \frac{|\text{Observed - Expected}|}{\text{Expected}} * 100$$

Oblique Breaks: Inter-Observer Percent Error

Mean = 25.31	% Error	+/- Degree
Observer 2	4.64%	1.173160173
Observer 3	5.75%	1.454545455
Observer 4	11.33%	2.867965368

Results

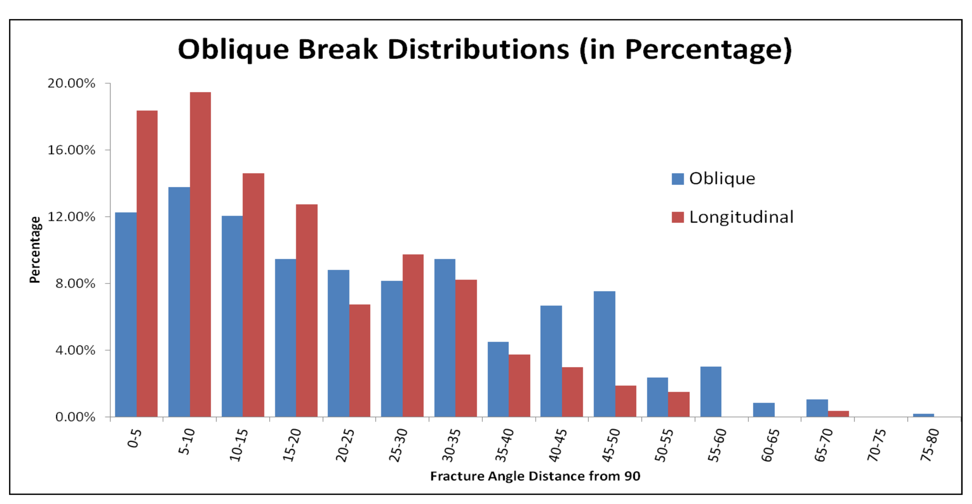
All Elements

The entire hammer stone assemblage consists of 466 oblique , 268 longitudinal, and 31 transverse breaks. Per the results of Alcantara-Garcia et al (2006) and Pickering et al (2005), the transverse breaks were not analyzed and the main focus is on oblique breaks.

A Student's t-test comparing the oblique and longitudinal breaks showed that **there is a significant difference between fracture angle group means (*p<.0001*)**, which does not support the null hypothesis that there is no difference between fracture angles for oblique and longitudinal breaks.

It does, however, support the notion that the different break orientations will yield different means at the assemblage level; in this case **the fracture angles on longitudinal breaks are closer to 90 degrees than those on oblique breaks**. Therefore, as demonstrated by Alcantara-Garcia et al (2006) and Pickering et al. (2005), it is necessary to analyze each breakage assemblage separately, and only oblique breaks are compared henceforth.

- Unfused/fusing and fused bones (p=.4999), as well as long bone shafts and epiphyses (p=.779), are statistically the same.
- Limb portion and age have no impact on breakage results in this study



By Skeletal Element

Perhaps the most informative breakdown in terms of breakage dynamics is the element comparison. Each long bone's fracture angles are compared to all other long bones and t-tests are run for each comparison. The results of the **t-tests for fracture angles on oblique breaks show that there are no significant differences between the humerus and femur**, **but there are between those two elements and the rest of the long bones**. Thus, the null hypothesis that all long bone elements will produce fracture angle samples that are statistically the same is not supported. This suggests that bone shape, density, and cortical bone thickness influence the breakage dynamics for each long bone.

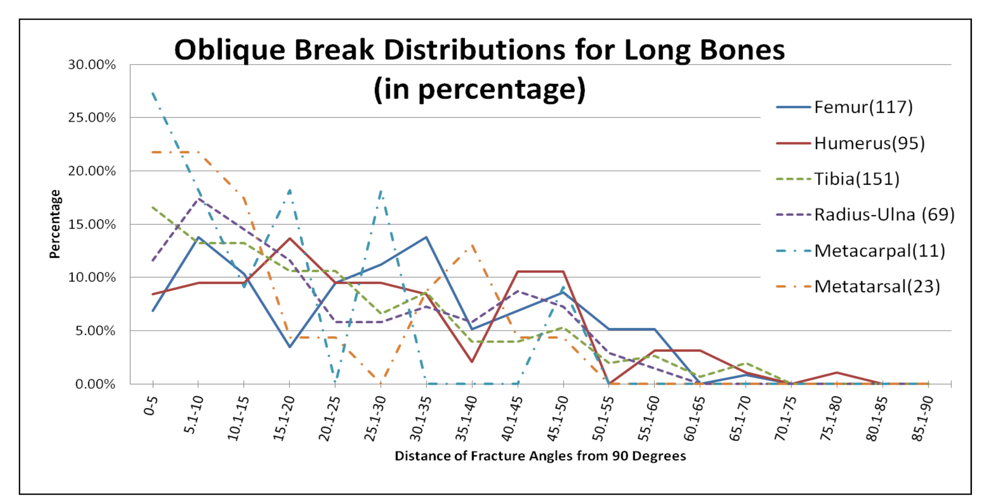
Oblique Break Comparisons for Long Bone Elements

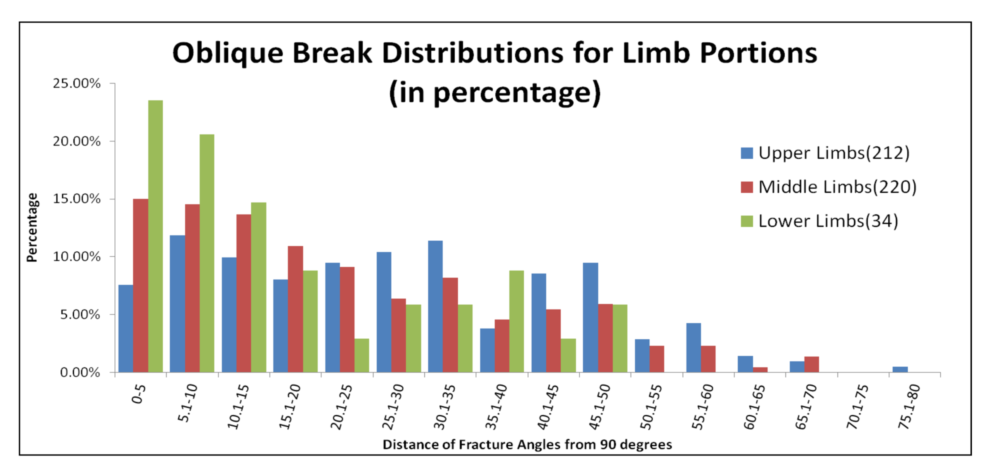
ANOVA: p=**0.001352**	Femur	Humerus	Tibia	Radius	MTC	MTT
Femur	t-test	0.653773	0.994408	0.782508	0.491041	0.57943
Humerus	0.89687		0.640152	0.417298	0.396222	0.427728
Tibia	**0.00463**	**0.012966**		0.640884	0.486555	0.570805
Radius	**0.022247**	**0.042492**	0.954124		0.622419	0.794244
MTC	**0.022415**	**0.034012**	0.236918	0.21966		0.77772
MTT	**0.005234**	**0.010099**	0.199226	0.197419	0.799389	F-test

Oblique Break Comparisons for Long Bone Limb Portions

	Upper	Middle	Lower
Upper	t-test	0.617639	0.253411
Middle	**0.000438**		0.365173
Lower	**0.000452**	0.079383	F-test

When comparing limb portions (categorized as upper, middle, or lower), a similar pattern is apparent. **The upper limb bones (femur and humerus) show significant differences when compared to the middle and lower limb bones.** There is no significant difference between the middle and lower limb bones. This also does not support the null hypothesis that all limb bones will have fracture angle samples that are statistically the same. The histogram shows a similar, closer to right-angled distribution for the middle and lower limb bones and a quite different and more oblique distribution for upper limb bones, which suggests that the less round, denser, and thicker cortical bone breaks at angles closer to 90 degrees.

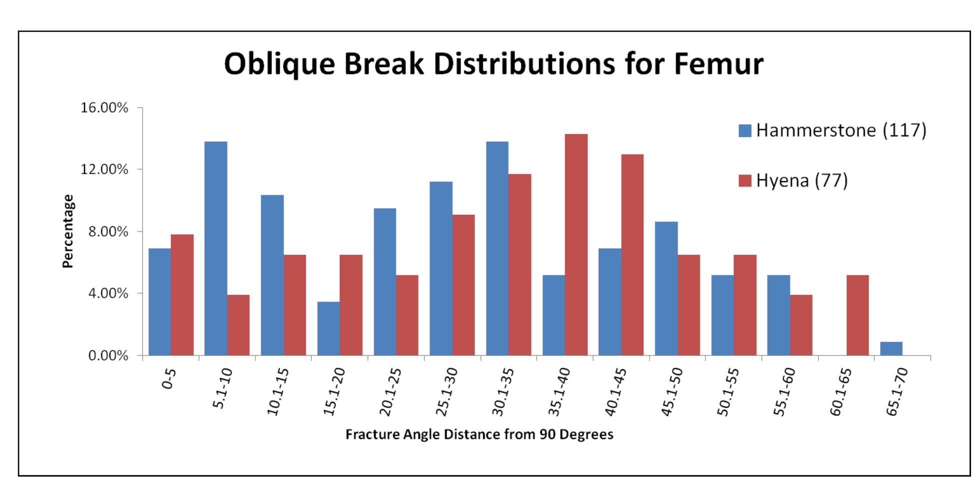




Hammerstone versus Hyena

The comparison between the two groups of broken femora, the t-test of the **oblique breaks resulted in a significant difference between the two assemblages, rejecting the null hypothesis that both hyena and hammerstone breakage assemblages will be the same**.

- A hyena chewed on 11 femora at the Milwaukee Zoo
- Hyena sample compared to the hammerstone femora produced significant differences between the groups
- **Hyena breaks averaged angles further from 90 degrees than the hammerstone sample**
- Opposite of what Alcantara-Garcia et al (2006) found for both their large and small mammal sample



Goniometer versus 3D Model Measurements

We are also exploring new technologies which will allow more accurate and reliable measurements using digital models of bone fragments. We scanned twenty long bone fragments with a NextEngine scanner and Scanstudio software, then imported them into Geomagic to make 3-dimensional digital models. Seven angle measurements were taken along the entire length of the break at equal increments from the center angle measurement. The boundary between the cortical surface and the break surface formed the vertex of the fracture angle. The two additional points defining the angle were each taken 2.5 mm from the vertex onto the cortical surface and the break surface. The 3D method potentially offers a more precise (and perhaps more consistent) way of measuring fracture angles and produces more data that drives us towards the question: Is the center of the break the most representative of the entire break and the best place to measure?

Our sample is still very small, but there is no significant difference between the 3D midpoint measurements and the goniometer measurements. However, **there is a significant difference between the break average derived from all seven angles taken along each break and the center goniometer measurements, though this is not as surprising since break edges can be quite variable.** In general, the 3D model means are closer to 90 degrees in both the midpoint and average measurements than the goniometer measurements. There are disagreements between how angles are divided by eye and by the computer, since the computer may pick up contours of the bone that are not as visible to the eye (and vice versa), which can alter the data. Also, the curvature and the length of the break strongly influence the differences between the 3D and goniometer measurements, since even the smallest deviations from the exact center can lead to different angles.

Goniometer versus 3D Measurements

n = 20	Goniometer	3D Center	3D Average
Mean	84.18	92.7	88.11
Mean from 90	25.68	18.33	16.44
F-Test *p*-value		0.31656	0.106145
T-Test *p*-value		0.310021	0.620348
F-Test *p*-value from 90		0.980787	0.299539
T-Test *p*-value from 90		0.093863	**0.021647**

Conclusions

Carnivore and hammerstone fracture angle distributions on oblique breaks overlap strongly; at the assemblage level carnivore fracture angles are slightly more oblique than those of hammerstones. This runs contrary to the results of one study (Alacantra et al 2006), but concurs with a study on equid bone fracture angles (de Juana and Dominguez-Rodrigo, 2011).

- **No significant difference between:**
  - Juvenile and adult assemblages
  - Long bone epiphyses and shaft fragments
  - Goniometer and 3D mid-break measurements
- **Significant differences between:**
  - Fracture angles on oblique and longitudinal breaks
  - Upper limb bones and other limb bones.
  - Hammerstone and carnivore fracture angles
  - Goniometer mid-break measurements and 3D average measurements

Based on the results of the analysis, there are several points to be made about future use of fracture angles for determining breakage agents. As stated in other research articles (Alacantra et al. 2006) and reaffirmed here, many of the most interesting differences arise from oblique break comparisons, potentially stemming from the idea that longitudinal breaks are inherently more right angled than oblique breaks, which is suggested by our data. Also, bones break differently based on their bone shape and cortical bone thickness and density, which tends to increase distally, therefore it is important to compare bones to at least limb portion, if not the specific element themselves. This can be problematic for archaeological assemblages where the long bone shaft fragments are not as easily identifiable to element, but if they are identified to limb portion, the comparisons should still hold true. Including measurable angles from epiphyses, which are more identifiable, will also improve the results.

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