Improving Zooarchaeological Methods for Classifying Fragmented Faunal Remains using Differential Geometry and Machine Learning

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Nazarbayev University

- **The Bone Breakage Research Team:** Jeff Calder, Reed Coil, Peter Olver, Cheri Shakiban, Martha Tappen, Anthony Yezzi, Jr., Katrina Yezzi-Woodley
- Pedro Angulo-Umaña, Jacob Elafandi, Bo Hessburg, Riley O'Neill, Jacob Theis
- **Anthropology Laboratory Manager:** Matt Edling
- **Scanning:** Advanced Imaging Service for Objects and Spaces (AISOS) (Sam Porter and Colin McFadden), Center for Magnetic Resonance Research, Department of Radiology (CMRR) (Todd Kes and Cassandra Koldenhoven), Anthropology Computer Laboratory, anthropology undergraduate interns and volunteers
- **Funding Entities:** University of Minnesota Graduate Research Partnership Program (GRPP), Anthropology Department block grants, NSF Grant DMS-1816917
- **Bone suppliers:** Elk Marketing Council, Crescent Meats
- **Volunteers (bone breaking):** Matt Edling, Ivy Faulkner, Theodore Wilson, Irena Wilson, Erin Crowley, TJ Paulli, Ranae Paulli, Brisa Yezzi-Woodley, Kilee Johnson, Kyra Johnson, Kameron Dropps, Riley O'Neill, Pedro Angulo-Umaña, Bo Hessburg, all the paleopicnic participants,
- **Hyenas:** Milwaukee County Zoo (Scruffy), Irvine Zoo, Wisconsin

Ancient Hominin Sites

Cradle of Humankind	Australopithecus	2.3 Ma
Olduvai Gorge	Homo habilis	1.9 Ma
Dmanisi, Georgia	Homo erectus	1.8 Ma
. . .		

Research Queries

I. How do the fragments go back together?

II. What broke them?

Fig. 4: the U of M anthropology lab, native habitat of Homo Anthropologis

Fig. 5: The annals of the U of M's Anthropology Department

Actor

Taxon

Element

Breaking Bones

Carnivore

Crocuta crocuta = *hyena*

Hominin

Batting

Hammerstone and anvil

Hammerstone only

Geological

Rock fall

Working Hypothesis

The geometry of the bone fragments,
their identity (taxon and element),
and how they are reassembled
will tell us the actor of breakage

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The geometry of the bone fragments,
their identity (taxon and element),
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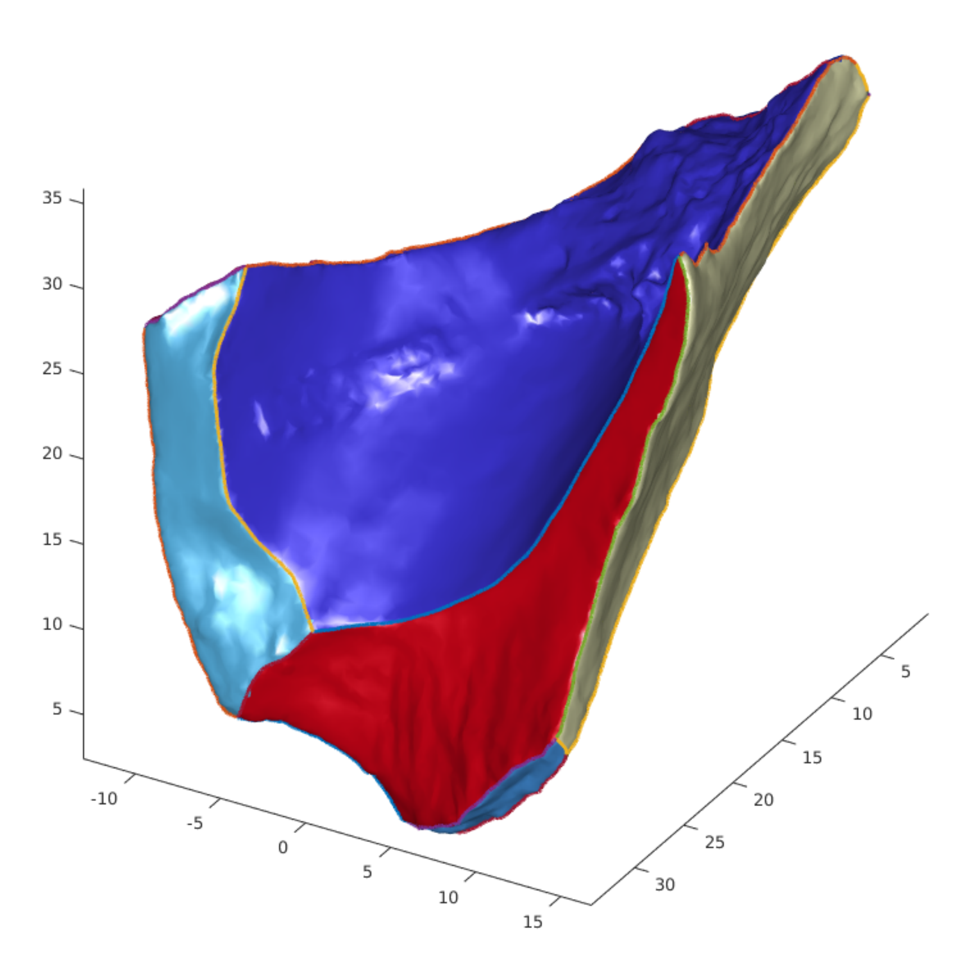
will tell us the actor of breakage

★ Break edges and break faces ★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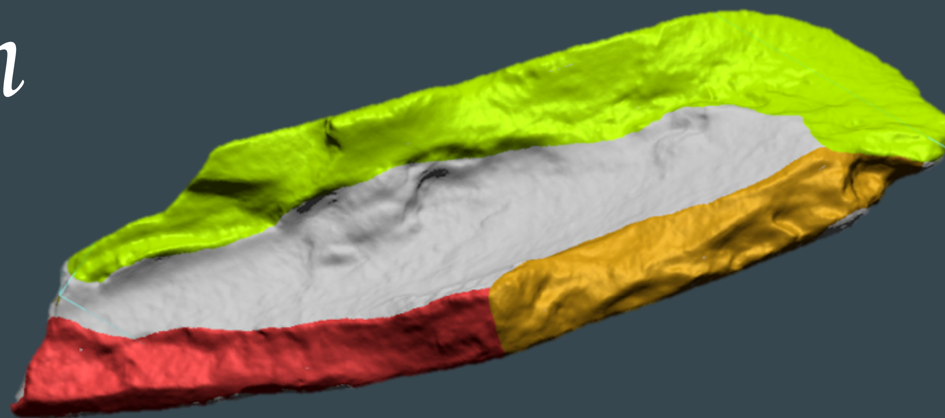
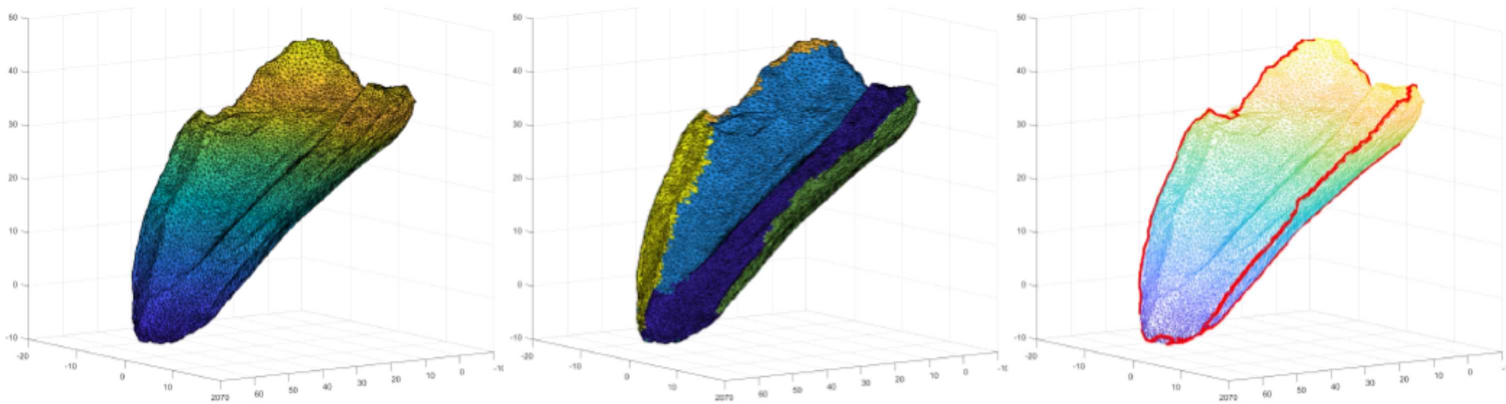
Segmentation





(a) Bone fragment (b) Face segmentation (c) Edge tracing

FIGURE 1: Results of preliminary experiments with face segmentation and edge tracing.

Archaeological importance of fragmentary bone

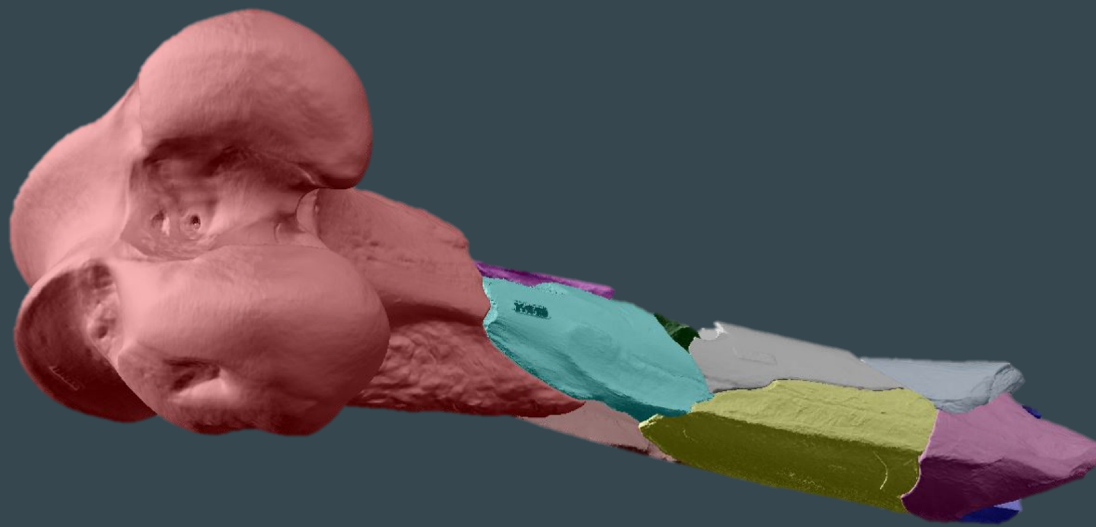
- Social structures
- Food sharing
- Home bases/central places
- Carcass transport
- Localized activity areas
- Scavenging vs. hunting
- Cooperative behavior
- Butchering behavior

OR
?

Question 1: Does bone fragment shape tell us anything about the actor responsible for fragmentation?

Question 2: If so, can we distinguish hominin damage from carnivore damage?

Further, can we identify different types of hominin damage?



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Machine Learning

Quaternary Science Reviews
Volume 139, 1 May 2016, Pages 43-52

When felids and hominins ruled at Olduvai Gorge: A machine learning analysis of the skeletal profiles of the non-anthropogenic Bed I sites

Mari Carmen Arriaza [a, b], Manuel Domínguez-Rodrigo [b, c]

Palaeogeography, Palaeoclimatology, Palaeoecology
Volume 488, 15 December 2017, Pages 103-112

On applications of micro-photogrammetry and geometric morphometrics to studies of tooth mark morphology: The modern Olduvai Carnivore Site (Tanzania)

Mari Carmen Arriaza [a, b], José Yravedra [b, c], Manuel Domínguez-Rodrigo [b, c, d], Miguel Ángel Mate-González [e, f], Elena García Vargas [c], Juan Francisco Palomeque-González [c], Julia Aramendi [b, c], Diego González-Aguilera [f], Enrique Baquedano [b, g]

Journal of Computational Science 32 (2019) 36–43
Contents lists available at ScienceDirect
Journal of Computational Science
journal homepage: www.elsevier.com/locate/jocs

Automated identification and deep classification of cut marks on bones and its paleoanthropological implications

Wonmin Byeon [a,f,1], Manuel Domínguez-Rodrigo [b,c,d,*,1], Georgios Arampatzis [a,e,1], Enrique Baquedano [b], José Yravedra [b,d], Miguel Angel Maté-González [g], Petros Koumoutsakos [a,e]

Archaeological and Anthropological Sciences
https://doi.org/10.1007/s12520-019-00815-6

ORIGINAL PAPER

Classifying agency in bone breakage: an experimental analysis of fracture planes to differentiate between hominin and carnivore dynamic and static loading using machine learning (ML) algorithms

Abel Moclán [1,2,3] • Manuel Domínguez-Rodrigo [3,4] • José Yravedra [4]

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RESEARCH ARTICLE

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Sebastián Block, Frédérik Saltré, Marta Rodríguez-Rey, Damien A. Fordham, Ingmar Unkel, Corey J. A. Bradshaw

SCIENTIFIC REPORTS

OPEN

Distinguishing butchery cut marks from crocodile bite marks through machine learning methods

Manuel Domínguez-Rodrigo [1,2] & Enrique Baquedano [1,3]

Received: 20 November 2017
Accepted: 19 March 2018

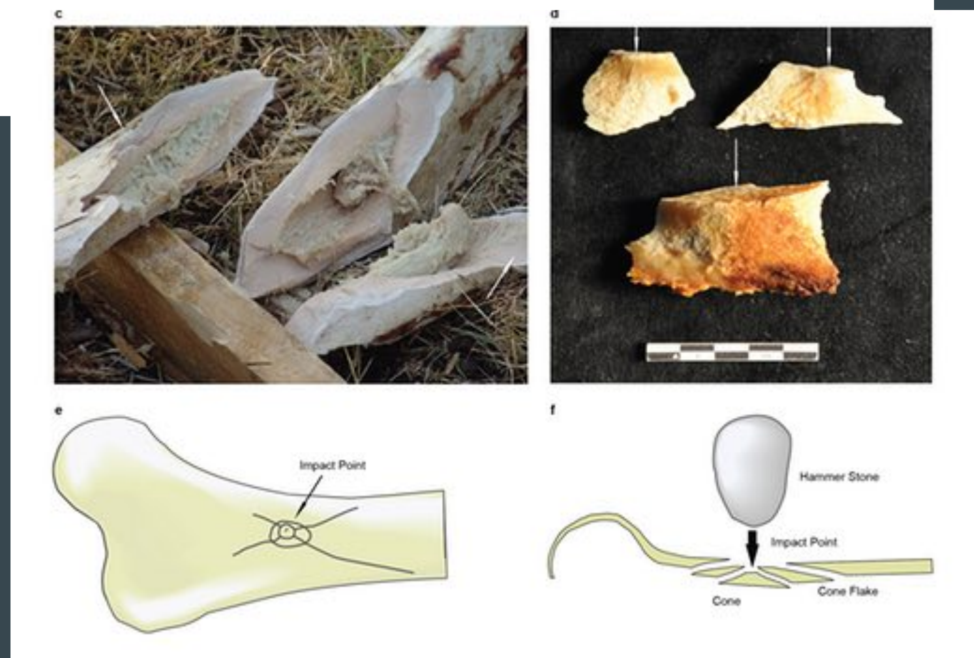
theguardian

Could history of humans in North America be rewritten by broken bones?

Smashed mastodon bones show humans arrived over 100,000 years earlier than previously thought say researchers, although other experts are sceptical

Ian Sample Science editor

Wednesday 26 April 2017 13.00 EDT



Laelaps

Busted Mastodon Is Ice Age Roadkill

A mastodon said to be pulverized by Ice Age humans was probably busted up by roadwork

By Brian Switek on April 10, 2019

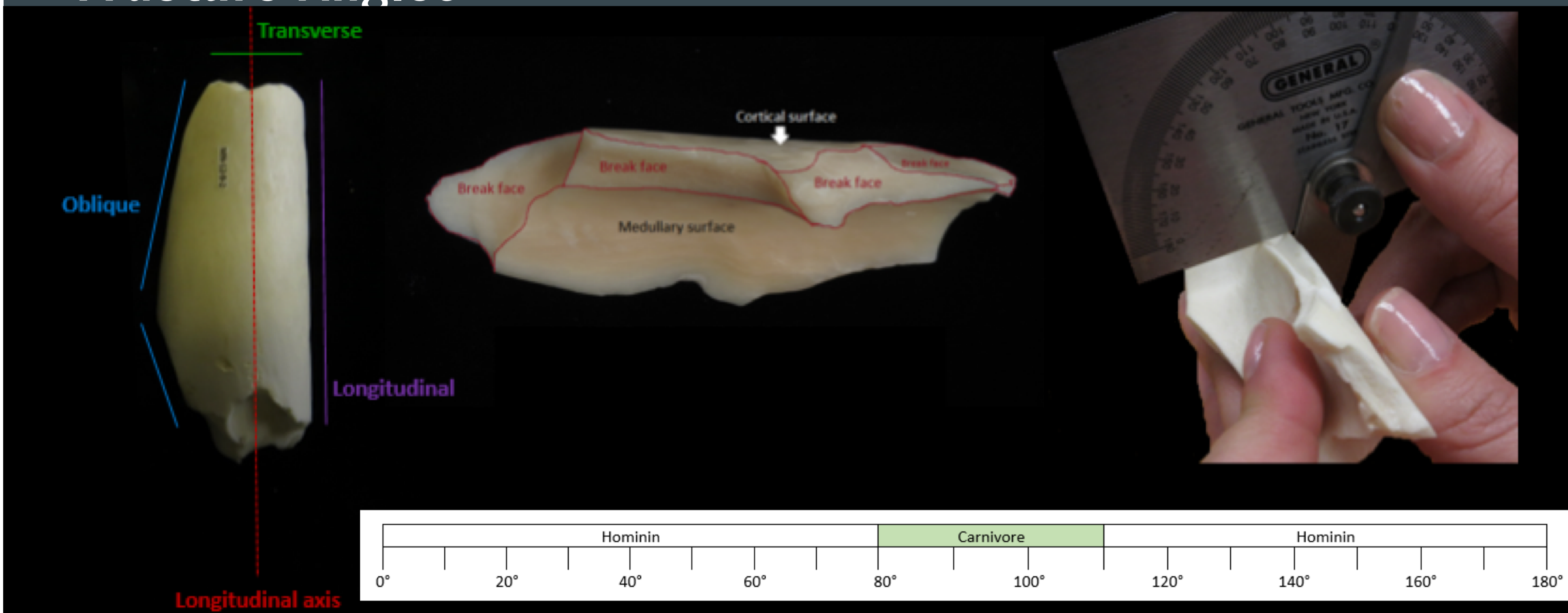
LATEST NEWS

How Climate-Friendly Would Flying Cars Be?

Studies on bone breakage

- Fracture Outline
- Fracture Plane
- Quality of Fracture Edge
- Remaining Circumference
- Fracture Freshness Index (FFI)
- Fragment Length, width, breadth-to-length ratio
- Notch dimensions
- Fracture Angle

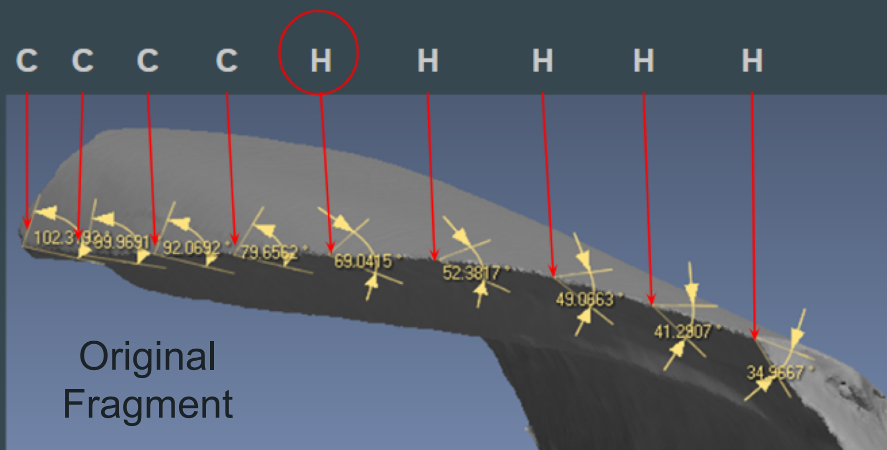
Fracture Angles

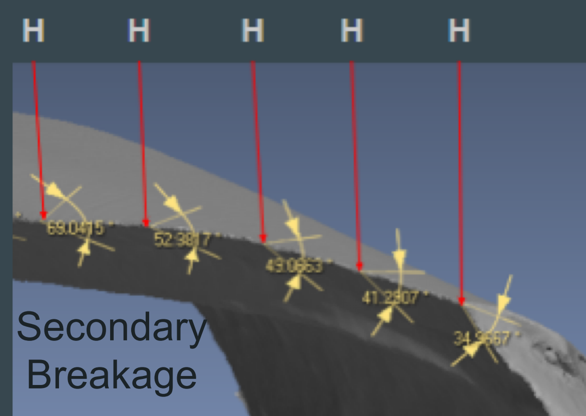


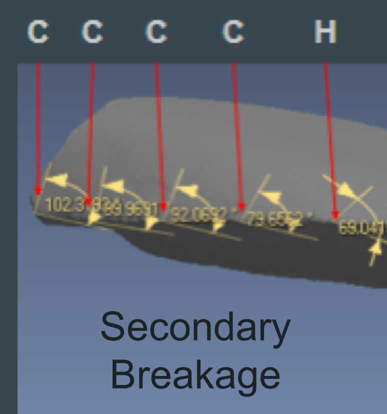
Alcantara-García et al. (2006).

Mixed results

< 80° = hominin
80° and 110° = carnivore
> 110° = hominin







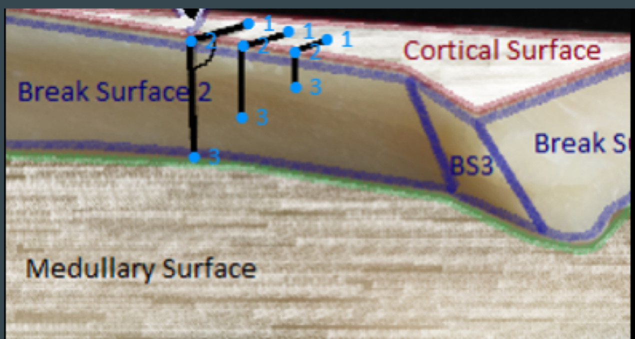
Average = 49° (hom)
Min = 35° (hom)
Max = 102° (carn)
Center = 69° (hom)

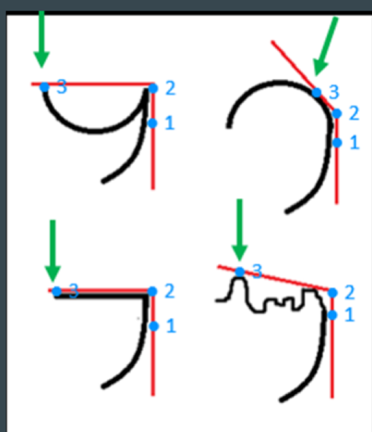
Average = 49° (hom)
Min = 35° (hom)
Max = 69° (hom)
Center = 49° (hom)

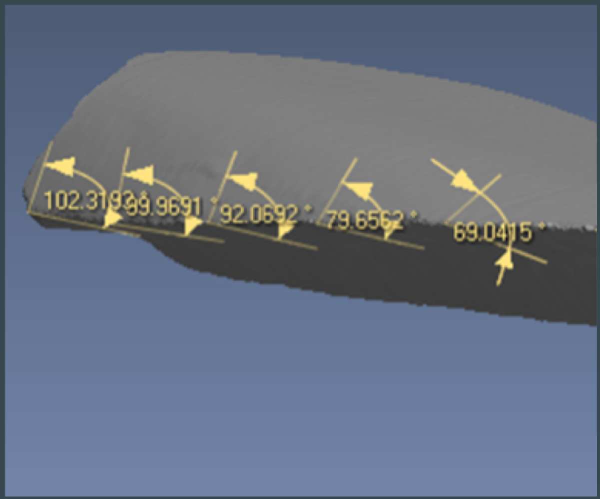
Average = 89° (carn)
Min = 69° (hom)
Max = 102° (carn)
Center = 92° (carn)

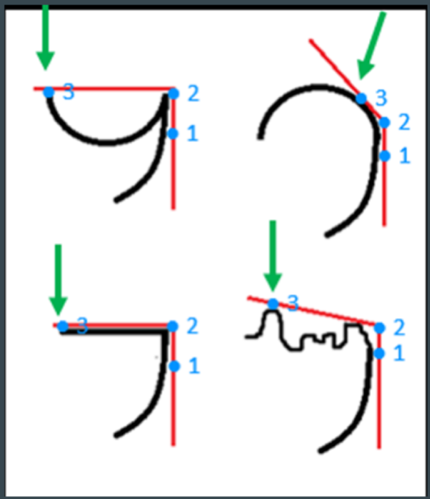
"Midpoint measurements were the chosen standard because the fracture angle of a plane often varies along its full length."(Pickering et al., 2005:251)

Fracture Angles: Methods






102.3193
99.9691
92.0692 °
79.6562 °
69.0415 °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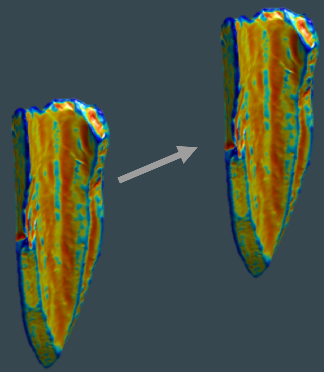
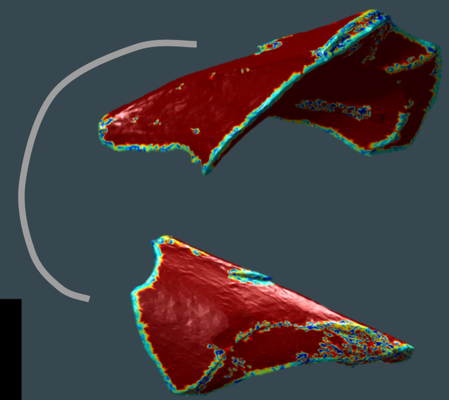
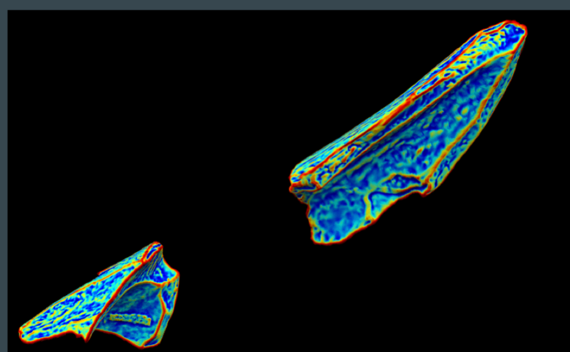
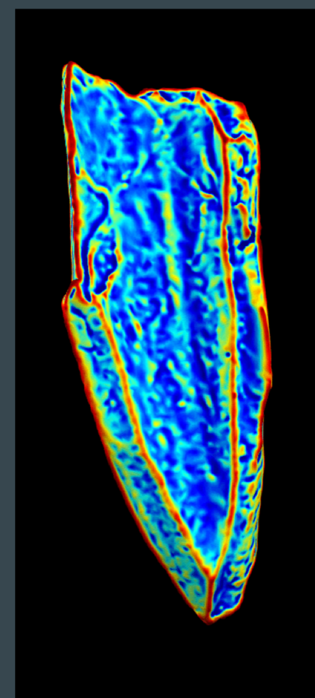
New mathematical tools . . .

Rigid motions (group theory)



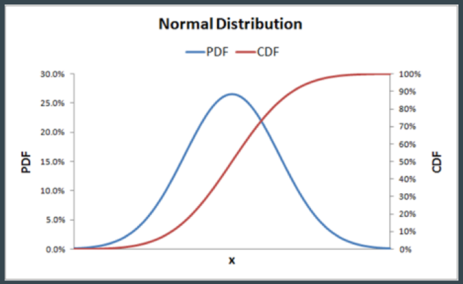




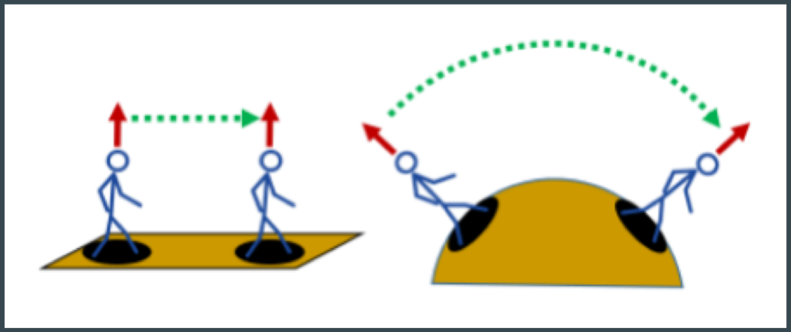


Geometric Invariants

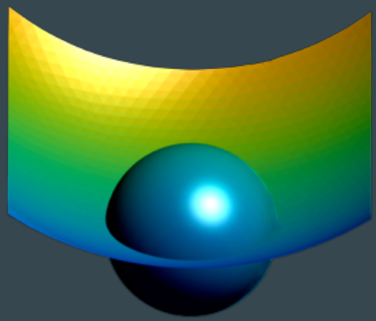
Distance histograms



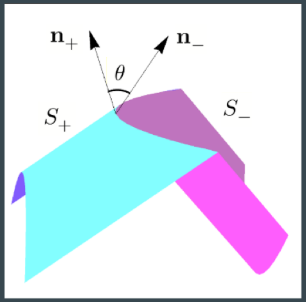
Surface curvature



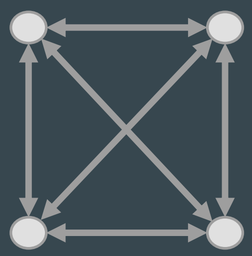
Spherical volume invariant



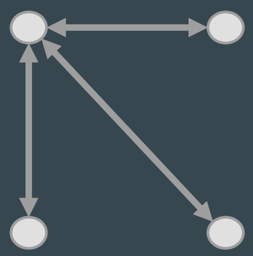
Virtual goniometer



Distance histograms

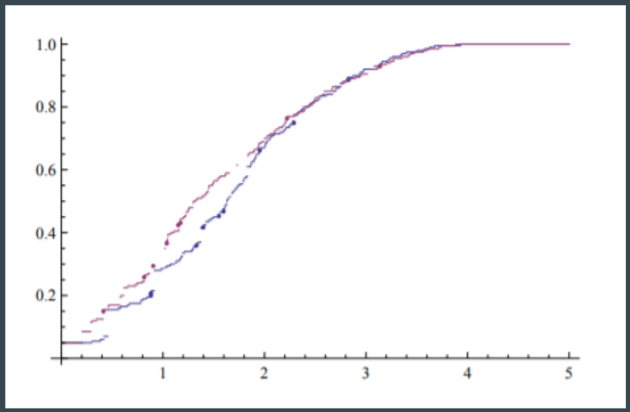


Pairwise

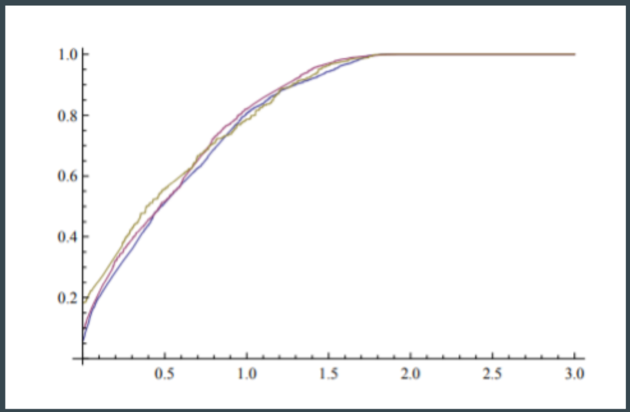


Fixed point

Trapezoid vs. Kite

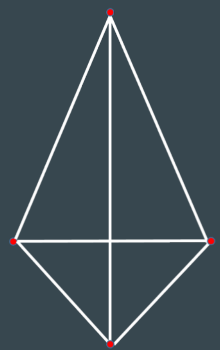


Rectangle vs. Rectangle

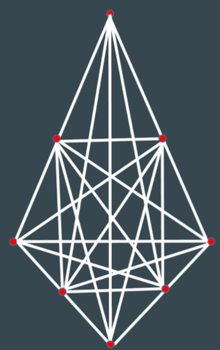


(Brinkman and Olver, 2012)

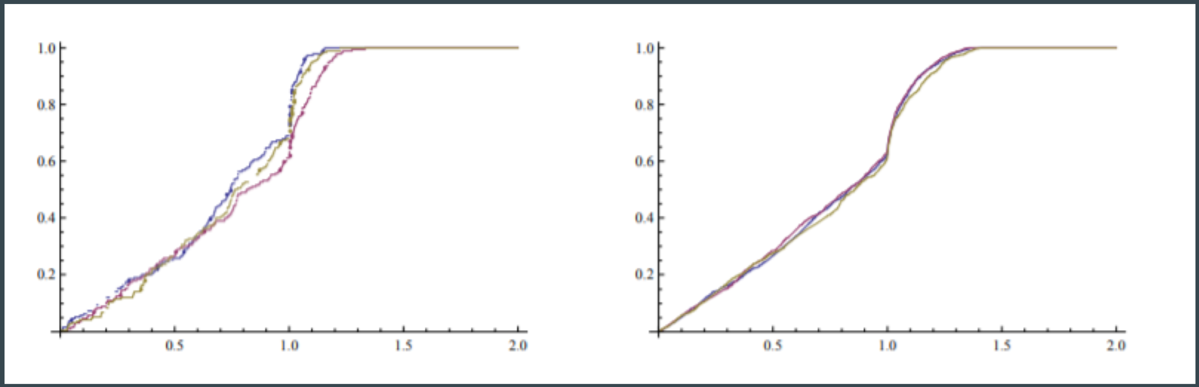
Distance histograms



n = 4



n = 8

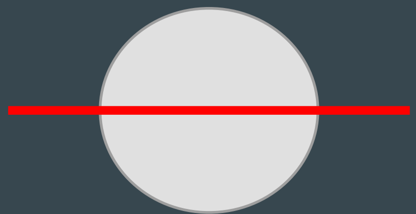


n = 20

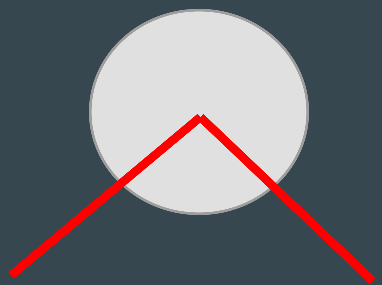
n = 50

(Brinkman and Olver, 2012)

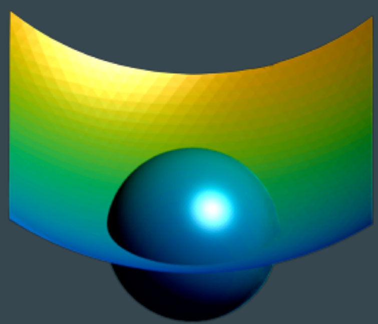
Spherical Volume Invariant (SVI)



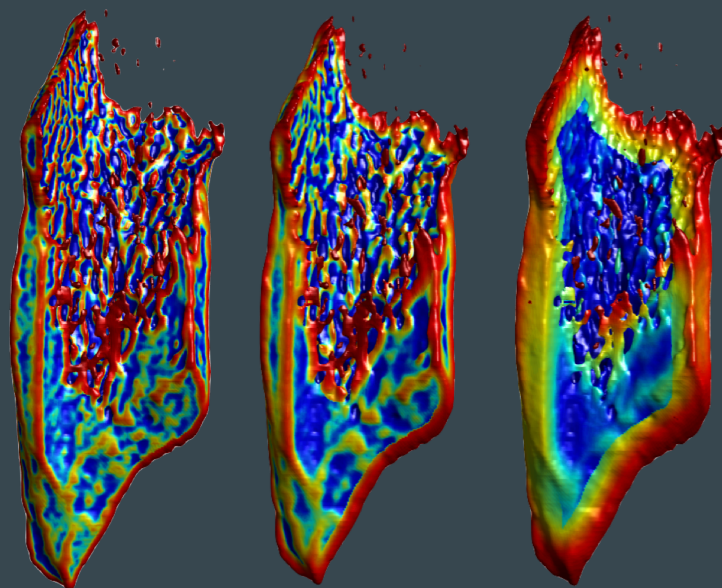
Example A



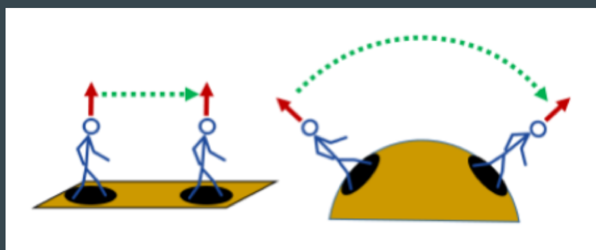
Example B

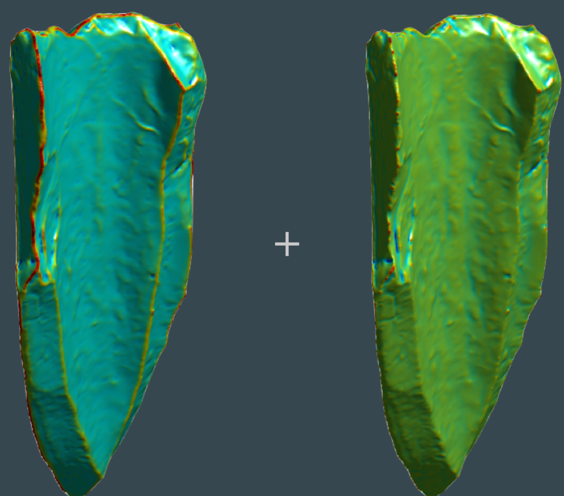


Volume at r = .5, 2, 5   Red = least, blue most (normalized by fragment), shows varying degrees of feature detection

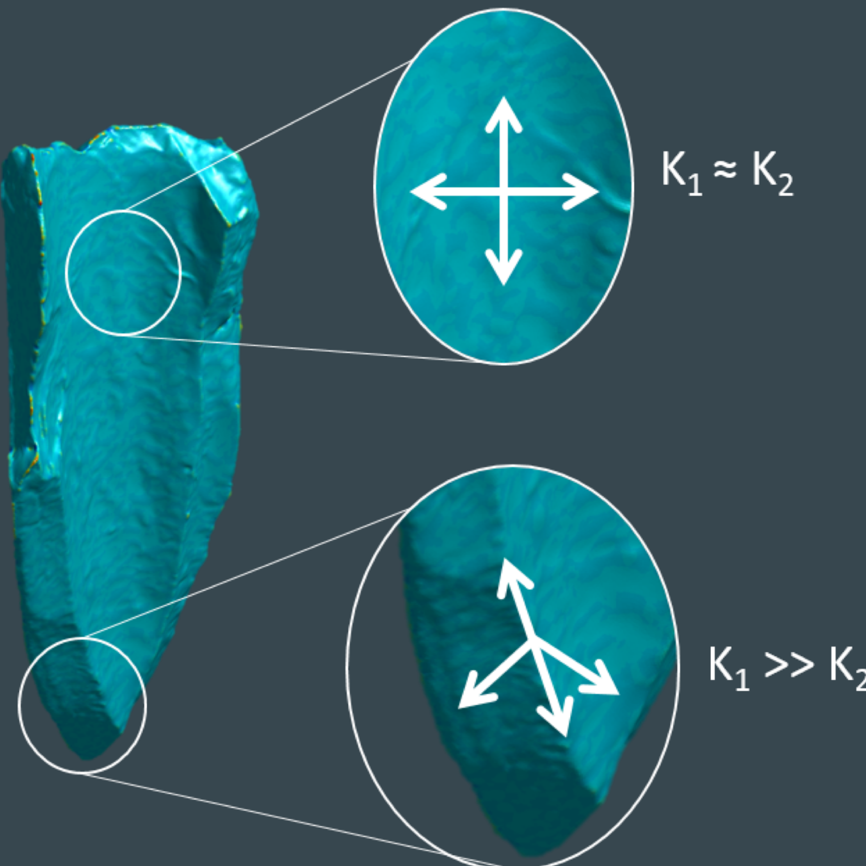


Surface Curvature

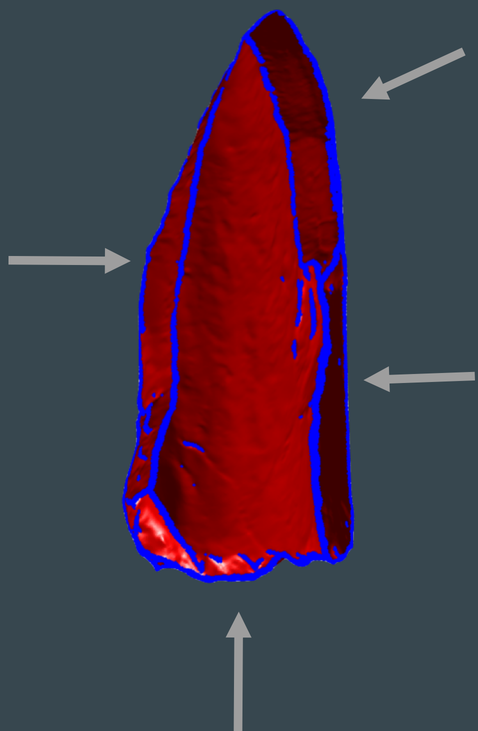




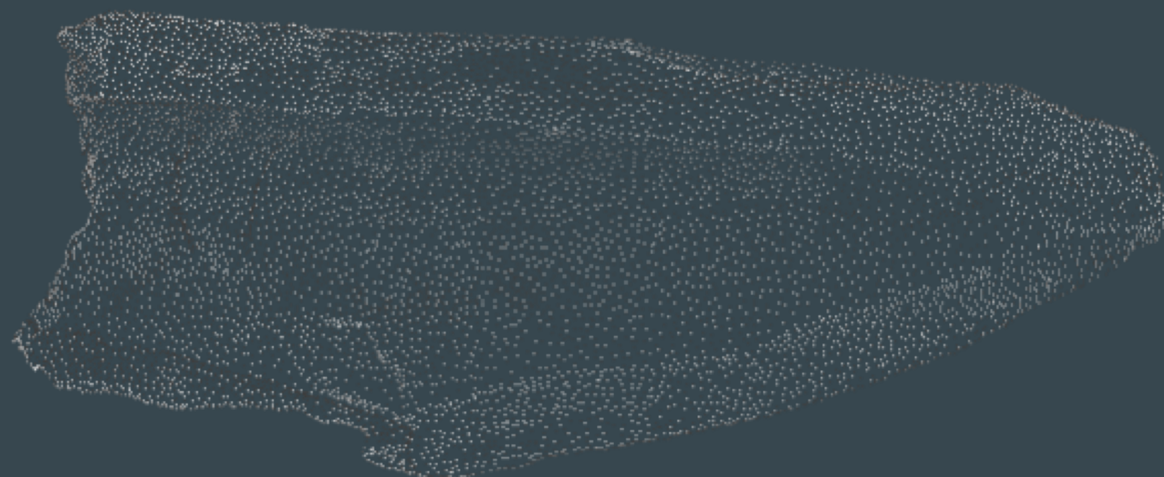
K_1 + K_2



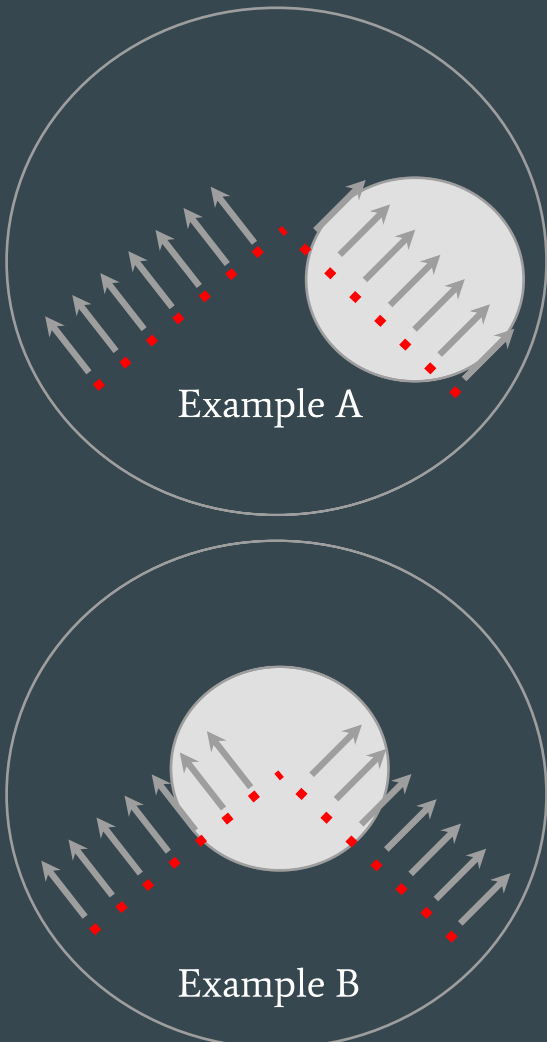
Much Richer Data

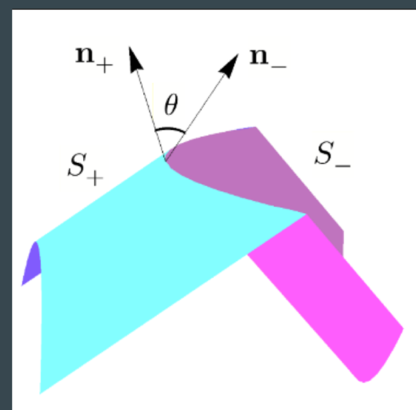


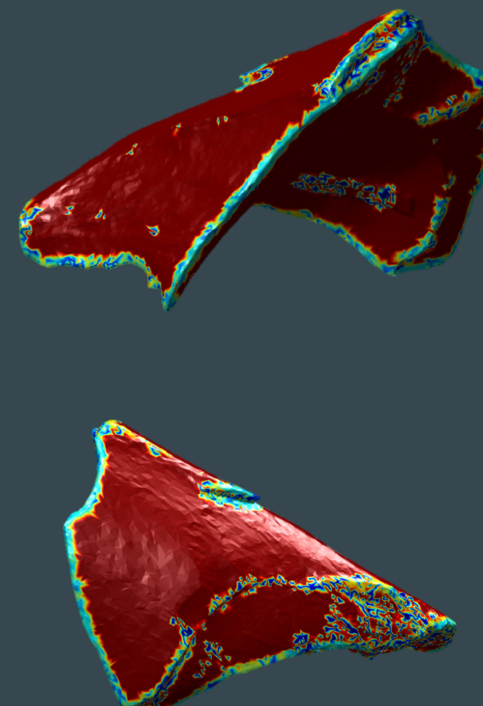
OR



Virtual Goniometer







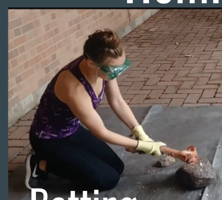
Preliminary results

Agents of fragmentation and equifinality

Carnivore

Crocuta crocuta

Hominin



Batting

Hammerstone and anvil

Hammerstone only

Geological

Taxa

- Cervus canadensis
- Odocoileus virginianus
- Capra hircus
- Ovis aries
- Bos taurus
- Equus caballus

Skeletal Elements

- Femur
- Tibia
- Humerus
- Radius-ulna
- Metapodials

Sample Size (Digital Data)

	Femur	Humerus	Radius-Ulna	Tibia	Total
Crocuta	411	120	0	64	595
Hominin	363	291	287	333	1274
Rockfall	0	85	105	0	190
Total	774	496	392	397	2059

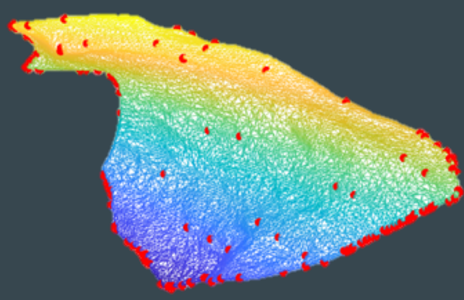
Manual Data

- 457 fragments
- 2,059 breaks
- 1,358 measurements

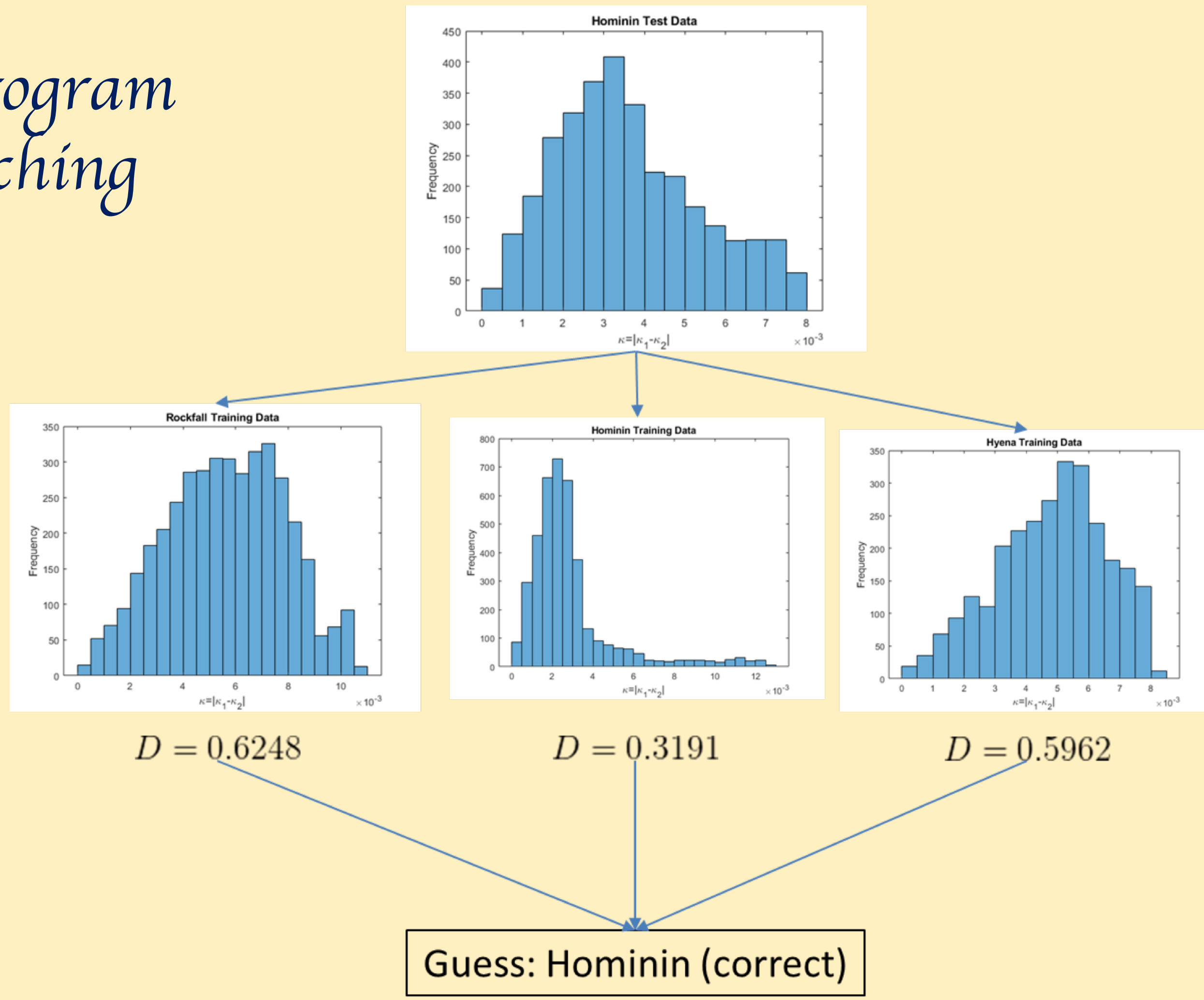
Digital Data

- 82 fragments
- 1,376,900 measurements
- 1% = 13,769

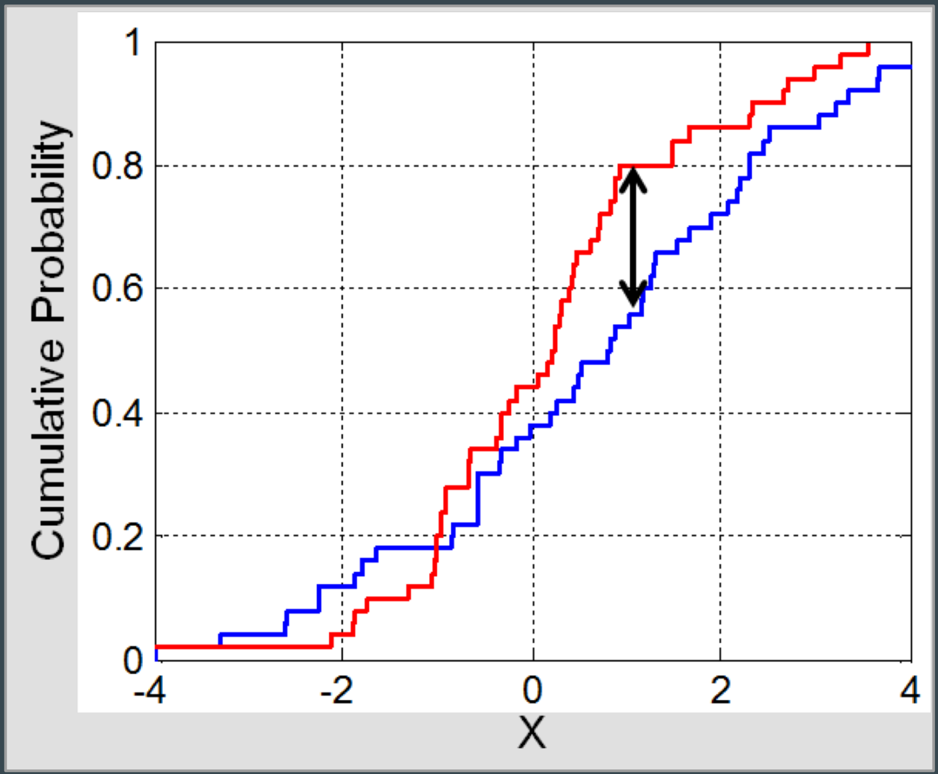
	Femur	Humerus	Tibia	Radius-Ulna	Total
Batting	1,758	606	1,878	1,531	5,773
Crocuta	1,824	780	-	-	2,604
Hammerstone & Anvil	1,485	1,003	1,291	1,613	5,392
Total	5,067	2,389	3,169	3,144	13,769



Histogram matching



First Stages



Training set

(Hyena)

Test set

(Hominin)

Test set

(Hyena)

NO

YES

Results

Curvature Test Results

Tests: >50
Test sets: 40% - 75%
(152 - 1824 curvature extractions)
Trials per test: 1,000
True positives: 0.938 - 0.965
True negatives: 1.00
False negatives: 0.00
False positives: 0.035 - 0.062

Manual Test Results

Tests: 15
Test sets: 40% - 75%
(22 - 157 fracture angles)
Trials per test: 1,000
True positives: 0.949 - 0.966
True negatives: 0.034 - 0.051
False negatives: 0.019 - 0.561
False positives: 0.439 - 0.981

Preliminary conclusion: Geometric invariants might perform better than traditional measures.

hominin vs. hyena (femur) – surface curvature

Yes category	yes Size	No category	no Size	Training percentage	Training Size	Sensitivity	Specificity	Precision	Negative Predictive Rate	Miss Rate	Fall out
hominin (femur)	3243	hyena (femur)	1824	75	811	0.942	1	1	0.94518	0.058	0
hyena (femur)	1824	hominin (femur)	3243	75	456	0.95	1	1	0.95238	0.05	0
hominin (femur)	3243	hyena (femur)	1824	65	1136	0.947	1	1	0.94967	0.053	0
hyena (femur)	1824	hominin (femur)	3243	65	639	0.939	1	1	0.94251	0.061	0
hominin (femur)	3243	hyena (femur)	1824	50	1622	0.949	1	1	0.95147	0.051	0
hyena (femur)	1824	hominin (femur)	3243	50	912	0.946	1	1	0.94877	0.054	0
hominin (femur)	3243	hyena (femur)	1824	40	1824	0.946	1	1	0.94877	0.054	0
hyena (femur)	1824	hominin (femur)	3243	40	1095	0.938	1	1	0.94162	0.062	0

Hominins vs. hyena (femur) – manual data

Yes category	yes Size	No category	no Size	Training percentage	Training Size	Sensitivity	Specificity	Precision	Negative Predictive Rate	Miss Rate	Fall out
hominin femur	261	hyena femur	177	75	66	0.956	0.368	0.60202	0.8932	0.044	0.632
hyena femur	177	hominin femur	261	75	45	0.957	0.222	0.55159	0.83774	0.043	0.778
hominin femur	261	hyena femur	177	65	92	0.959	0.502	0.6582	0.92449	0.041	0.498
hyena femur	177	hominin femur	261	65	62	0.966	0.294	0.57775	0.89634	0.034	0.706
hominin femur	261	hyena femur	177	50	131	0.963	0.561	0.68688	0.93813	0.037	0.439
hyena femur	177	hominin femur	261	50	89	0.966	0.299	0.57948	0.8979	0.034	0.701
hominin femur	261	hyena femur	177	40	157	0.949	0.494	0.65223	0.90642	0.051	0.506
hyena femur	177	hominin femur	261	40	107	0.956	0.327	0.58686	0.8814	0.044	0.673

Sample Size (Manual Data)

Number of breaks per element and actor of breakage

	Femur	Humerus	Radius-Ulna	Tibia	Total
Crocuta	411	120	0	64	595
Hominin	363	291	287	333	1274
Rockfall	0	85	105	0	190
Total	774	496	392	397	2059

Number of breaks per element and actor for which no goniometer measurement could be taken

	Femur	Humerus	Radius-Ulna	Tibia	Total
Crocuta	234 (57%)	32 (27%)	-	13 (20%)	279 (47%)
Hominin	102 (28%)	51 (18%)	64 (22%)	153 (46%)	370 (29%)
Rockfall	-	21 (25%)	31 (30%)	-	52 (27%)
Total	336 (43%)	104 (21%)	95 (24%)	166 (42%)	701 (34%)

Number of breaks per element and method of breakage

	Femur	Humerus	Radius-Ulna	Tibia	Total
Batting	159	144	130	186	619
Crocuta	411	120	-	64	595
Rockfall	-	85	105	-	190
Hammerstone & Anvil	175	137	122	147	581
Hammerstone only	-	10	-	-	10
Hominin mixed method	29	-	35	-	64
Total	774	496	392	397	2059

Number of breaks per element and method for which no goniometer measurement could be taken

	Femur	Humerus	Radius-Ulna	Tibia	Total
Batting	41 (26%)	29 (20%)	22 (17%)	95 (51%)	187 (30%)
Crocuta	234 (57%)	32 (27%)	-	13 (20%)	279 (47%)
Rockfall	-	21 (25%)	31 (30%)	-	52 (27%)
Hammerstone & Anvil	57 (33%)	19 (14%)	35 (29%)	58 (39%)	169 (29%)
Hammerstone only	-	3 (30%)	-	-	3 (30%)
Hominin mixed method	4 (14%)	-	7 (20%)	-	11 (17%)
Total	336 (43%)	104 (21%)	95 (24%)	166 (42%)	701 (34%)

Moving Forward

- Continue to develop scanning and post-processing methods that are useful for large assemblages.
- Complete the experimental breakage
  - Adding in the additional taxa
  - Adding in the additional methods of breakage including rockfall
- Continue to take manual measurements and apply virtual goniometer
- Incorporate other geometric invariants
- More advanced ML protocols — SVM, KNN, CNN, random forests, etc.
- THE ARCHAEOLOGICAL SAMPLE - Dmanisi
- Also, automated refits (Yezzi-Woodley talk)