Morphological characteristics of healthy and osteoarthritic joint surfaces in archaeological skeletons

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Running head: Joint Morphology and Osteoarthritis

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Tables: 6
Supplementary figures: 1

Abstract:

Osteoarthritis is a major health concern in living populations, as well as being one of the most common pathological lesions identified in the archaeological record. The aetiology of the disease remains unclear, with a multi-factorial influence of physical strain, age, genetics, and obesity. Previous studies have identified a relationship between the presence of knee osteoarthritis on the distal femoral joint and the morphology of the intercondylar notch, patellar groove, and medial condyle. The current study expands this research to investigate the relationship between distal femoral, distal humeral, and proximal ulnar joint morphology and osteoarthritis with 3D shape analysis techniques. These methods provide a more detailed analysis of joint morphology in order to determine any relationship between 3D shape and osteoarthritis. The results indicate a complex relationship between joint shape and knee osteoarthritis, with eburnated right femora showing a statistically significant association. The shapes associated with eburnated or affected femoral joints can be explained by osteophyte development, and therefore likely represent systematic shape changes and not a particular joint shape predisposing individuals to the condition. There was no identifiable relationship found in the proximal ulna or distal humerus, indicating that joint shape is unlikely to influence the development of the condition in the elbow joint, and that any shape changes produced by osteoarthritis are not systematic or quantifiable. The joints analysed in this study were highly influenced by asymmetry, sexual dimorphism, and allometry, resulting in a small sample size of affected joints in many datasets. Further analyses of large skeletal samples are needed to more thoroughly investigate the possible relationship of distal femoral joint shape and osteoarthritis.

Introduction:

Osteoarthritis receives a great deal of attention in both palaeopathological and clinical studies due to its high frequency in human populations past and present (palaeopathological literature: Weiss & Jurmain, 2007; Waldron, 1991; Lieverse et al., 2006; clinical literature: McGonagle et al., 2010; Zhai et al., 2007; Hootman et al., 2003). Despite its prevalence, the aetiology of osteoarthritis continues to elude researchers. The main theories to date are biomechanical breakdown of the joint due to physical stress, degeneration associated with increasing age, and a genetic predisposition (Molnar et al., 2009; Herrero-Beaumont et al., 2009; Spector et al., 1996). Osteoarthritis can also develop as a consequence of acute injury; this condition is often referred to as 'secondary osteoarthritis', as opposed to 'primary' or idiopathic osteoarthritis (Cymet & Sinkov 2006; Honkonen 1995). It is now generally accepted that osteoarthritis is a multifactorial disease with multiple aetiological factors contributing to the overall degeneration or break-down of the joint structure (Spector & MacGregor, 2004; Weiss, 2006).

Knee osteoarthritis is very common (Rogers et al., 1990; Weiss & Jurmain, 2007). Felson et al. (1987) found a prevalence rate of 44% in individuals over 80 years of age having knee osteoarthritis in the Framingham Heart Study cohort, USA. Osteoarthritis of the elbow has been considered uncommon, with clinical prevalence reported at 1.3 – 7% (Dalal et al., 2007). However, elbow osteoarthritis has been found to be more prevalent in archaeological samples, with Debono et al. (2004) reporting 27% of individuals affected from a Medieval necropolis in Provence, France. This difference could be due to the condition being under-reported clinically, the use of different diagnostic criteria (clinical: radiographs, CT scans; archaeological:

macroscopic analysis of dry bone), or differences in physical activities between living and past populations (Debono et al., 2004).

Although the majority of osteoarthritis research focuses on the articular cartilage, the idea that other joint components (i.e. ligaments, subchondral bone) also play an important role in the development and progression of osteoarthritis has been gaining credibility (Karsdal et al., 2008; Tan et al., 2006; Hunter et al., 2005; Bailey et al., 2004). Bone morphology is influenced by epigenetic factors, as well as biomechanical stress during growth or remodeling (Pearson & Lieberman, 2004; Ruff, 2000). However, subchondral bone has less plasticity when it comes to physical influences than the diaphyseal cross-section or trabecular architecture (Ruff & Runestad, 1992), suggesting that, in the absence of pathology, the joint geometry developed during childhood is retained throughout adulthood (Frost 1994a,b). There is a complex relationship between genetics and physical stress and the development of osteoarthritis and it is hypothesized that the morphology of the joint itself, influenced by genetics and biomechanical necessity, may influence the development or progression of osteoarthritis by contributing to the overall stability and functionality of the joint compartment (Wada et al., 1999; Shepstone et al., 1999, 2001). The current study aims to identify a possible relationship between joint morphology of the knee and/or elbow with osteoarthritis. The specific joints, the distal femur, distal humerus, and proximal ulna, were chosen because they undergo different physical stress and strains which would likely impact the relationship between joint morphology and biomechanics.

Previous research in this area is limited. Rettig et al. (2008) used metric analyses on radiographs of 90 elbows of living patients from Indiana, USA to identify any morphological characteristics of the distal humerus which may predispose individuals to osteoarthritis. However, they found no statistically significant relationships. Shepstone et al. (1999, 2001)

performed a 2D shape analysis using geometric morphometrics on the inferior aspect of the distal femoral joint of 101 adult femora from the archaeological skeletal collection of St. Peter's Church, Barton on Humber, UK (Waldron & Rodwell, 2007). They were able to identify a relationship between distal femoral shape and osteoarthritis, with the eburnated joints having narrower U shaped intercondylar notches, wider medial condyles, and shallower patellar grooves. The authors suggest that the shape difference of the intercondylar notch may be a risk factor for developing osteoarthritis but suggest further research is needed (Shepstone et al., 2001). Wada et al (1999) performed a traditional morphometric analysis on patients and cadavers, and also found a correlation between narrow intercondylar notches and the progression of osteoarthritis. Their results suggest that osteophyte development in the intercondylar notch occurs to stabilize the anterior cruciate ligament (ACL) in the early stages of osteoarthritis.

This paper expands the previous work by analyzing the full 3D morphology of the distal femur, distal humerus, and proximal ulna from archaeological skeletal populations to identify possible correlations of joint shape with osteoarthritis. The secondary aim of this paper is to investigate the potential of using 3D geometric morphometric techniques in osteoarthritis studies, as they could also be employed in clinical research. These methods will enable a more detailed and accurate investigation of the relationship between joint shape and osteoarthritis than is possible with traditional or 2D morphometrics. As Shepstone et al (1999, 2001) and Wada et al. (1999) have found a correlation between joint morphology and osteoarthritis in the distal femur, it stands to reason that osteoarthritis may also correlate with the morphology of the distal humerus and proximal ulna. The null hypothesis to be tested is one of no relationship between joint morphology and osteoarthritis. If this is refuted and a relationship exists, it could indicate a joint morphology which influences the development and/or progression of osteoarthritis.

Materials and Methods:

One hundred and forty-seven individuals, producing a total of 155 ulnae, 200 humeri, and 105 femora, from four archaeological English populations dating from the 4th-19th centuries AD were analysed. These populations were chosen based on the large number of well preserved adult skeletons. The number of joints per individual studied was dependent on preservation (Table 1, Table 2).

The presence or absence of eburnation was recorded and the location was reported to differentiate between joint compartments affected (e.g. tibio-femoral, femoro-patellar, radio-capitellar, ulno-trochlear). Osteophytes were recorded according to size (</> 2mm from the original joint margin) and according to the percentage of the joint margin covered (Figure 1). The presence of porosity and the percentage of a joint surface covered were also recorded and the location of any joint contour change was recorded (Rogers & Waldron 1995). As there is disagreement in palaeopathology as to which joint changes should be used to diagnose osteoarthritis (Weiss & Jurmain, 2007; Waldron, 1991; Rogers & Waldron, 1995; Schrader, 2012; Rothschild, 1997), joints with pathological changes were divided into two groups. The first group is comprised of only those joints displaying eburnation with osteophytes, porosity, and/or joint contour change. The second group is comprised of joints displaying eburnation, or two or more of osteophytes, porosity, and joint contour change (based on Rogers & Waldron, 1995). For simplicity, the first group is identified as 'eburnated' and the second is termed 'osteoarthritis'.

Three-dimensional Cartesian coordinates of landmarks were digitized on the joint surfaces using a Microscribe® GLS digitizing system (EMicroscribe Inc) (Figures 2a-c). Landmarks for the distal femur were based on those used by Stevens & Strand Viðarsdóttir

(2008). These landmark data were then superimposed using generalized Procrustes analysis (GPA), which removes all scale and translational variation from the data (Goodall, 1991); size information in the form of centroid size, was retained as an independent variable. Centroid size is the square root of the sum of the squared distances of each landmark from the centroid of the landmark configuration (Slice, 2007). Principal components analysis (PCA) is used to examine patterns of shape variance (O'Higgins & Jones, 1998; Mitteroeker & Gunz, 2009). Cross-validated discriminant function analysis (DFA) was used to determine the power of discrimination between healthy and osteoarthritic joints (White & Ruttenberg, 2007; Cardini et al., 2009). To obtain optimal discrimination between groups and reduce noise on higher principal components (PC), the number of PCs included in the cross-validated DFA was reduced using the method proposed by Baylac and Frieβ (2005) and analyses were run on PCs representing five percent or more of the total shape variance (Zelditch et al., 2004). Regression analyses assessed the influence of allometry, age, and sexual dimorphism joint morphology. Statistical analyses were then run on the regression residuals to analyze shape with and without these effects (Slice, 2007). MANOVAs and ANOVAs were performed to determine statistical significance of group differences, with level of significance set at $p<0.05$. Analyses were run in Morphologika© (O'Higgins & Jones 2006), MorphoJ (Klingenberg, 2008), the EVAN toolbox, R (R Development Core Team, 2010), and SPSS© (SPSS Inc.). Intra-observer error was tested with 6 repeated observations and the smallest distance between different joints was close to 1.5 times the greatest distance between the repeated observations, indicating that intra-observer error was unlikely to affect group classification (Neubauer et al., 2010).

Results:

Non-pathological influences of shape:

Table 3 summarizes the DFA scores associated with non-pathological influences of shape for healthy controls. Asymmetry was a major contributor to shape in all joints. Males have significantly larger joints than females based on centroid size (ANOVA $p<0.001$). Regression analyses revealed a linear relationship between shape and log centroid size in all joints, which was explained by sexual dimorphism and indicates that the main shape differences between sexes are allometric. There were no age-related joint shape changes identified.

Osteoarthritis:

Table 4 summarizes the prevalence rates of individuals and joints affected with eburnation and/or osteoarthritis. Males displayed substantially more eburnation and osteoarthritis than females. There was a pattern of increasing prevalence of eburnation and osteoarthritic joint changes with increasing age. The elbow is more often affected by eburnation than the knee and the proximal ulna is more often affected by any pathological change than are the other two joints.

Any relationship between joint morphology and pathological changes are minimal compared to asymmetry or sexual dimorphism, even after regression analyses. Attempts were made to cancel out the effect of these influences by removing the shape variables associated with asymmetry and sexual dimorphism. This was done by splitting the data into groups (side and sex) and scaling each individual joint to the mean shape of its associated group (sex or side), and then scaling those means to the overall mean of the sample. The results obtained through this method did not produce better discrimination of pathological joints, likely indicating how small the shape differences are compared to the impact of sexual dimorphism and asymmetry on joint

shape. Therefore, in order to minimise the effect of these non-pathological influences on the results, the data were divided into individual datasets for sex and side. Unfortunately, this division of the data resulted in small sample sizes of affected joints in many datasets.

Regression analyses identified allometry as a contributing factor to joint shape even after sub-division of data, and as osteophyte development would affect the size of the joint, all data were regressed on log centroid size. Table 5 summarizes the results of the cross-validated DFA scores of the regression residuals for all eburnated joints compared with healthy controls. Table 6 summarizes the cross-validated DFA scores of the regression residuals for all osteoarthritic (including eburnated) joints compared with healthy controls. The scores for all analyses in these tables are based on PCs representing five percent or greater of the total shape variance.

Affected ulnae were not accurately classified based on the shape variables. Of the distal humeri, only the female left joints were accurately classified. However, MANOVAs found the difference between the groups to be non-significant and the affected joints do not group from healthy on the initial PCs (Figure S1). This indicates that the affected joints do not represent an identifiable group based on shape variables.

The distal femur shows the strongest separation of both eburnated and osteoarthritic joints. Affected male and female right femora were accurately classified and found to be statistically different ($p<0.022$) for both pathological groupings (Figure 3). There were no female left femora with eburnation, but the joints with osteoarthritis (no eburnation) were statistically different from healthy joints ($p=0.006$) and tend to group at the positive end of PC5 and PC6 (Figure 4). Eburnated male left femora were accurately identified with the cross-validated DFA, but a MANOVA did not find a statistically significant difference from healthy joints. This could

be a result of the small sample size of eburnated joints and a larger sample size may produce a significant result.

The wireframes illustrated in Figures 3 and 4 demonstrate the mean shapes of eburnated or osteoarthritic and healthy distal femoral joints. The main shape differences associated with affected femora relate to the intercondylar notch, with eburnated right and osteoarthritic left female femora showing a relative narrowing of the notch compared to healthy joints (arrow 1). This is especially evident in the male right femora. Eburnated male right and osteoarthritic female left femora appear to have wider condyles than do healthy bones (arrow 2), although this difference is not apparent in female right femora. Eburnated right femora, both male and female, also display relatively deeper patellar grooves than healthy joints (arrow 3).

There is no pattern in the distal humeral data related to differences in morphology associated with humero-ulnar osteoarthritis and radio-humeral osteoarthritis. The sample size of affected femoral joints was too small to identify the presence of any pattern associated with femoro-patellar or femoro-tibial osteoarthritis, as only two joints (one male left and one female right) displayed femoro-patellar osteoarthritis, and the others displayed femoro-tibial osteoarthritis. Of the male right femoral joints, two had eburnation on the medial condyle, while one had eburnation on the lateral condyle.

Discussion:

The results indicate a tentative relationship between distal femoral joint shape and osteoarthritis, with the right femora showing statistically significant shape differences between eburnated and healthy joints. There was also a significant difference between female left joints which displayed osteoarthritic changes without eburnation (i.e. osteophytes, porosity, joint

contour change) and healthy joints. However, there was no relationship identified for the male left femora when any osteoarthritic changes are considered. Also, the accuracy of identifying affected right femoral joints dramatically decreased when the diagnostic criteria was expanded to include joints with osteoarthritic changes without eburnation. The proximal ulnae and distal humeri showed no identifiable relationship between morphology and osteoarthritis. The null hypothesis, therefore, is supported for the elbow joints, but can be neither supported nor refuted for the distal femur.

The prevalence of knee osteoarthritis in this population was low and the affected sample size is too small to make any strong conclusions. The results, however, do suggest that the use of 3D shape analyses have the potential to identify a relationship between femoral joint morphology and osteoarthritis. Shepstone et al. (1999) and Wada et al. (1999) analysed all femora (side, sex) in a single dataset. As the current study identified asymmetry, sexual dimorphism, and allometry as major contributors to joint morphology, the relationship between distal femoral morphology and eburnation may be more complex than previously identified. The shape differences identified in the current study are similar to those reported by Shepstone et al. (1999) and Wada et al. (1999). Both male and female right eburnated femora, as well as female left joints with osteoarthritic changes without eburnation, had narrower intercondylar notches, although the inverted 'U' shaped notch described by Shepstone et al. (2001) was not apparent in these data. Eburnated male right and osteoarthritic female left femora also have wider medial condyles than healthy femora. However, Shepstone et al. (1999) found that eburnated femora had shallower patellar grooves, while the current study identified the groove as relatively deeper in eburnated right femora than healthy.

Many studies have identified a relationship between a smaller or narrower intercondylar notch and damage to the ACL (LaPrade et al., 1994; Good et al., 1991; Souryal et al., 1988) and Tan et al. (2006) found that ligaments may be one of the first joint components affected by the onset of osteoarthritis. Quasnichka et al. (2005) found that laxer ACLs were correlated with joint instability in guinea pigs and suggest that this predisposed the animals to osteoarthritis. They also found that the intercondylar notch underwent remodeling, becoming narrower, in response to the lax ACL. The narrow intercondylar notch identified in the current study could be a result of osteophyte development, as found by Wada et al. (1999), and may be a stabilization technique for a lax ACL (Quasnichka et al., 2005). However, this shape difference was not found in the male left femora and, with the exception of the female left femora, joints which displayed osteophytes without eburnation do not represent identifiable groups on the PCA charts. The joints showing systematic shape differences associated with the presence of eburnation could represent a difference in disease progression. The osteoarthritic joints lacking eburnation may represent an earlier stage of the disease and may therefore not have developed the shape changes identified with the eburnated right femora. Considering the findings of Quasnichka et al. (2005), the joints with narrow notches may represent a later stage of the disease whereby the joint has needed to respond with stabilization techniques. The present data are insufficient to answer these questions, but do indicate a possible avenue for future research.

The wider medial condyles identified in the male right eburnated and female left osteoarthritic (no eburnation) joints may also represent a stabilization technique, as suggested by Shepstone et al. (1999). Individuals with knee osteoarthritis display different femoral alignments and ranges of leg movements than healthy controls (Baliunas et al., 2002; Childs et al., 2004; Kaufman et al., 2001). These biomechanical differences would initiate adaptive remodeling in

the subchondral bone as a response to the physical stress (Ruff et al., 2006; Goldring & Goldring, 2010; Day et al., 2004). The medial condyle generally bears more weight than the lateral condyle (Lewek et al., 2004; Ruff, 1988) and undergoes more deformation during loaded flexion (Nambu et al., 1991). Therefore, it is possible that the wider medial condyles represent a functional adaptation to stabilize the joints during degeneration (Ruff et al., 2006; Dedrick et al., 1993; Shepstone et al., 1999, 2001). However, the eburnated female right joints do not show the same difference in medial condylar width. This may be an issue with sample size and the inclusion of more eburnated femora could provide better insight into how the joint responds to osteoarthritis.

There are morphological similarities between affected femoral joints, but these are not consistent throughout the data and therefore, do not support the hypothesis that joint morphology may be one factor predisposing individuals to osteoarthritis. The narrow intercondylar notch and wider medial condyles are likely influenced by new bone formation on the joint margins (osteophytes) as an adaptive response to stabilize the affected joint (Quasnichka et al., 2005; Wada et al., 1999; Shepstone et al., 1999). The present data suggest that eburnation is the osteoarthritic change most likely to influence femoral joint shape change or be influenced by a specific morphological type. The accuracy of identifying pathological right femoral joints is higher when only those with eburnation are considered in the analysis, and this accuracy decreases substantially when the analysis includes joints in the 'osteoarthritis' group. As the joints described as 'osteoarthritic' based on wider diagnostic criteria are not represented as identifiable groups, with the exception of the female left femora, the results may indicate that there are different factors influencing the variation in osteoarthritic joint changes.

These results also indicate the importance of clearly reporting the joint changes used to diagnose osteoarthritis. As only joints with eburnation tend to represent identifiable groups, it is suggested that palaeopathologists would benefit from differentiating between eburnated and non-eburnated osteoarthritic joints. The use of this categorization method into groups of osteoarthritic changes would provide reliable and accurate interpretations of osteoarthritic studies, even as the diagnostic criteria adapt with new research findings.

The results of this study support the findings of Rettig et al. (2008) in that there are no morphological characteristics associated with osteoarthritis on the distal humerus. This study also found no relationship between proximal ulnar morphology and osteoarthritis. Osteoarthritic elbow joints do not represent an identifiable sub-group within this skeletal population, indicating that joint morphology is unlikely to influence the development of osteoarthritis. Additionally, pathological changes do not result in a systematic alteration of the joint morphology.

It is unclear why the distal femur would show a relationship between joint morphology and eburnation while the elbow joints do not. It could be related to different biomechanical functions, as the knee is a weight-bearing joint and the elbow is not. In the absence of trauma or injury, the elbow joint is one of the most stable joints in the body (Morrey & An 2005; King et al., 1993). Perhaps osteoarthritis does not result in a systematic shape change because of this physiological stability, and therefore the joints do not undergo stabilizing remodeling to the same extent as the distal femur. Eckstein et al. (1993, 1994, 1995) used Finite Element analysis to determine the influence of joint morphology on stress distribution and found that the incongruity of the humero-ulnar joint, due to the deep trochlear notch, permits equal and bicentric distribution of stress (Merz et al., 1997). This indicates that the humero-ulnar joint is not predominantly affected by loading or stress in one area (such as the medial condyle of the femur)

and, therefore, any functionally adaptive changes would not result in a focused morphological change in one joint region. The lack of patterning in the data does not indicate that the shape of elbow joints are not changed by osteoarthritis; instead, the results indicate that the changes are not systematic and do not affect each joint in a predictable or quantifiable manner.

The main limitation relates to sample size. Joint shape is strongly influenced by factors unrelated to osteoarthritis, such as asymmetry and sexual dimorphism, and for best results the sample had to be divided by side and sex. The data from the distal femur indicate that these methods could possibly quantify joint shape related to osteoarthritis. This study provides a preliminary indication that 3D geometric morphometrics analysis of the knee joint related to osteoarthritis will benefit from further investigation. However, future research needs to include a larger sample to ensure that the number of joints for each side and sex are sufficient for statistical analysis.

Conclusion:

The current study was unable to identify specific distal humeral or proximal ulnar joint shapes which may predispose individuals to developing osteoarthritis. In addition, there was no pattern in the data associated with osteoarthritis, indicating that the condition does not alter the shape of these joints in a systematic manner. There was a tentative relationship between eburnation and distal femoral morphology, but it remains unclear whether the shapes identified predispose individuals to osteoarthritis or if osteoarthritis systematically alters the joint shape. The shapes associated with eburnation on the distal femur can be explained by functional adaptive responses to stress and therefore, may not represent a shape influencing the break-down of the joint components. The results indicate that further analysis with larger sample size may

identify an important relationship between distal femoral joint morphology and osteoarthritis. As these methods can be used in clinical situations to quantify shape on radiographs or CT images, future investigation into the relationship between distal femoral morphology and osteoarthritis could have clinical significance.

Future research should focus on larger sample sizes of pathological joints, especially in documented skeletal collections. Longitudinal clinical studies on living patients may indicate if the joint morphology is altered by osteoarthritis and how this relates to the progression of the disease. Associated physiological information, such as body mass and height, would also greatly expand the outcomes of this research.

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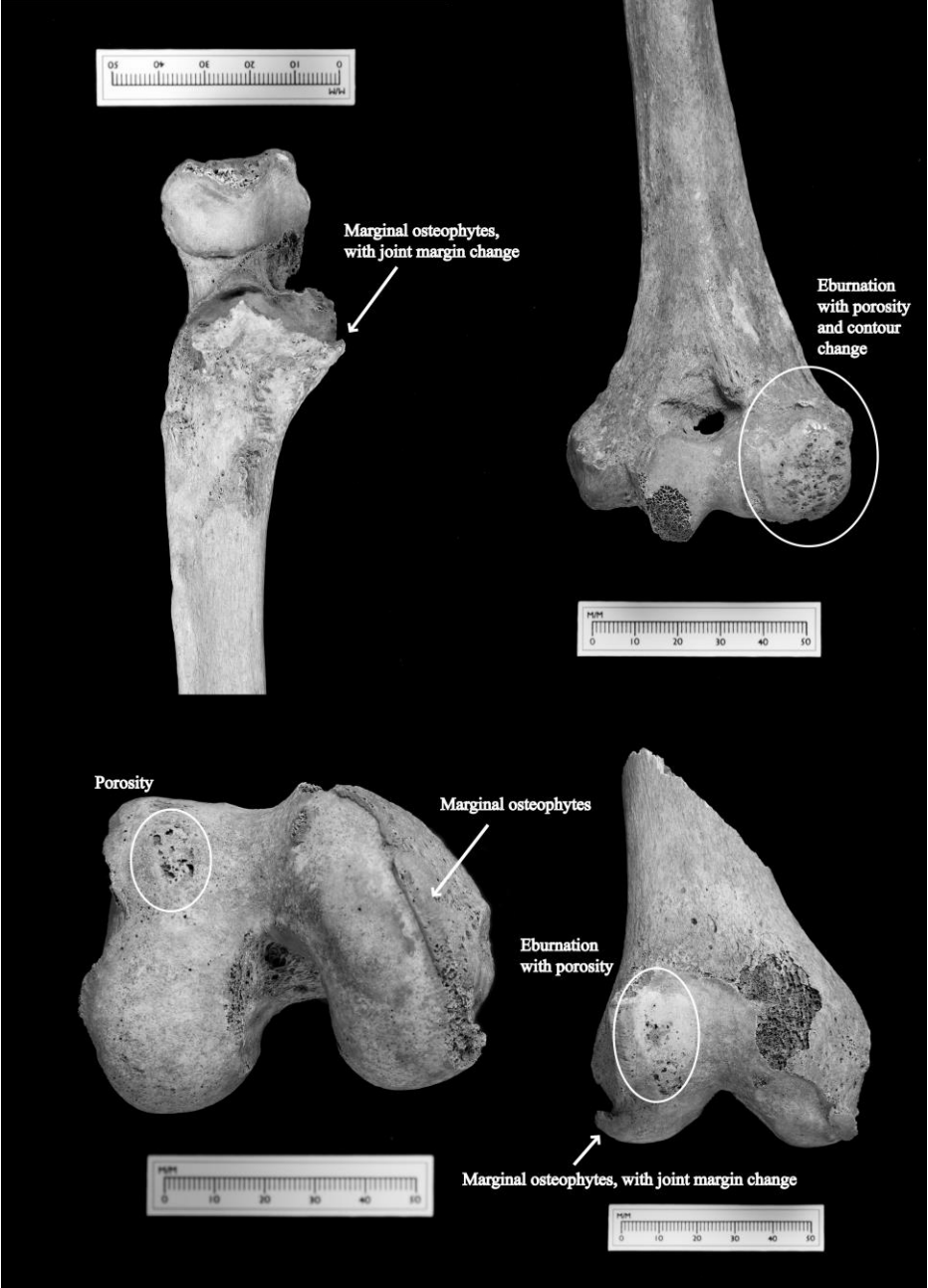
Figure 1) Examples of osteoarthritis with areas of eburnation with porosity circled and arrows indicating osteophyte formation. (Photographs by Jeff Veitch, Department of Archaeology, Durham University).
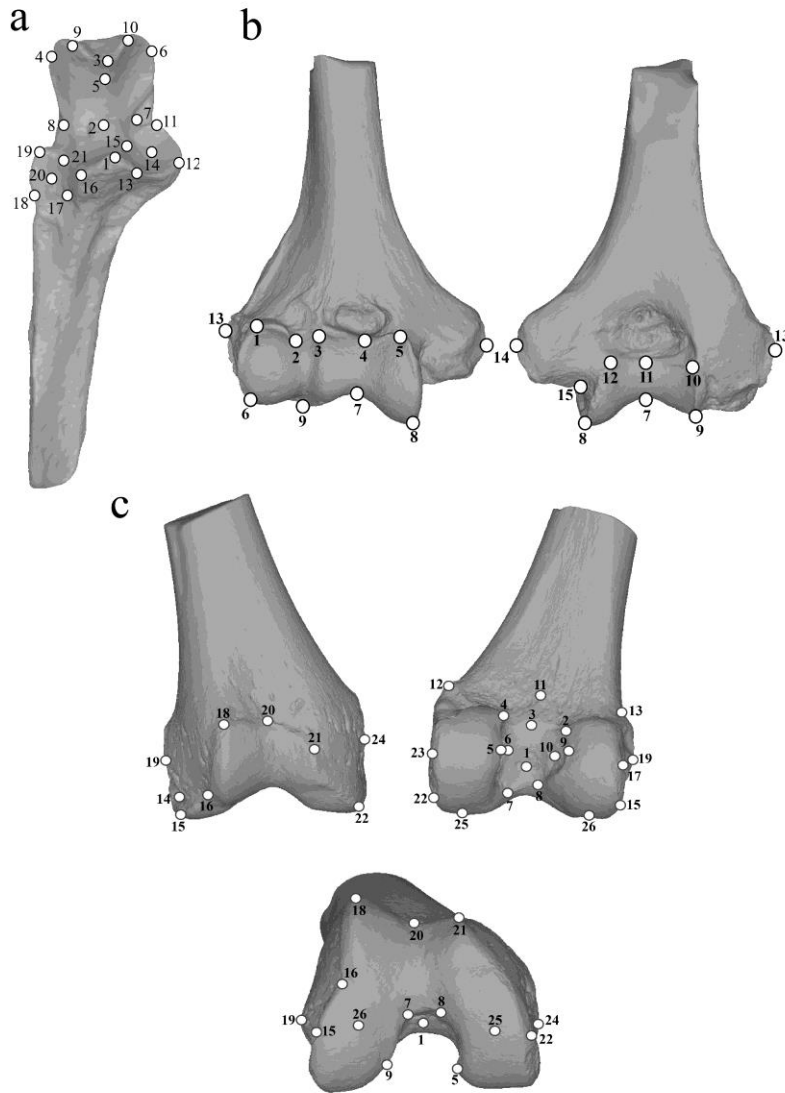
Figure 2) Locations of 21 landmarks digitized on the proximal ulnar joint (a), 15 landmarks digitized on the distal humeral joint (b), and 26 landmarks digitized on the distal femoral joint. (c).

Figure 3) PCA charts illustrating shape variability of (a) male right distal femora on PC1 and PC2, representing 27% total shape variance and (b) female right distal femora on PC3 and PC4, representing 21.5% total shape variance. Open squares represent healthy joints, open circles represent osteoarthritic joints (no eburnation), and filled circles represent eburnated joints. Wireframes illustrate the shape of mean healthy and eburnated joints.
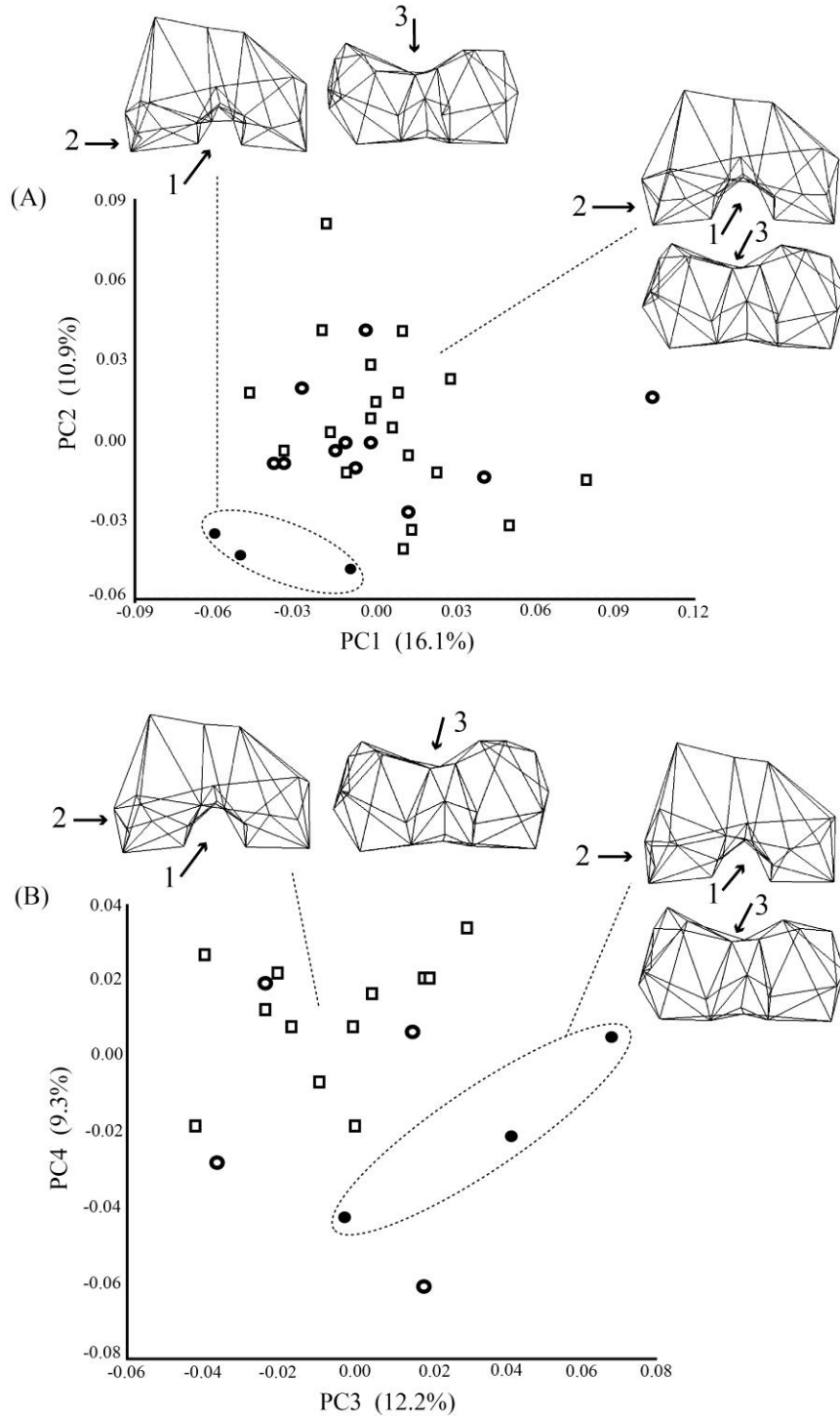
Figure 4) PCA charts illustrating shape variability of (a) male left distal femora on PC1 and PC2, representing 26.6% total shape variance and (b) female left distal femora on PC5 and PC6, representing 13.3% total shape variance. Open squares represent healthy joints, open circles represent osteoarthritic joints (no eburnation), and filled circles represent eburnated joints. Wireframes illustrate the shape of mean healthy and osteoarthritic (no eburnation) female left joints.
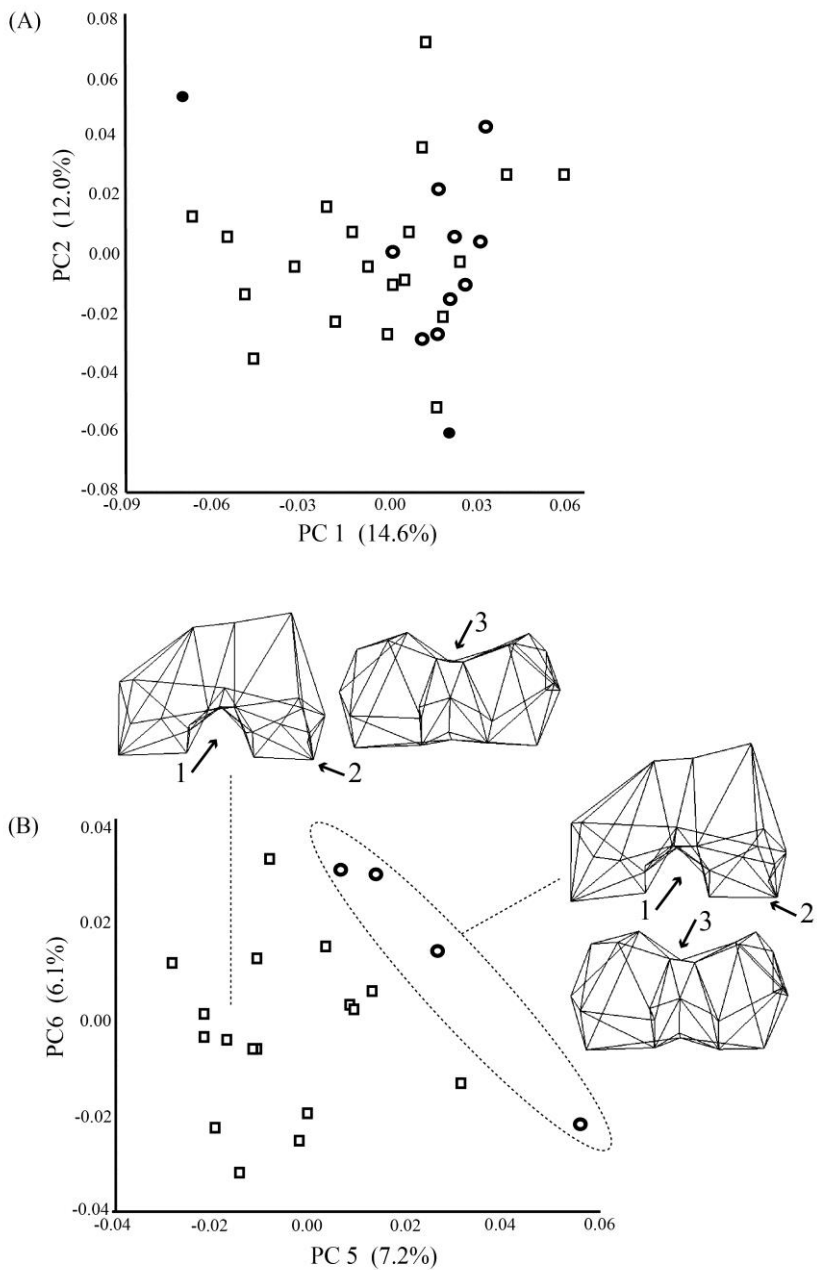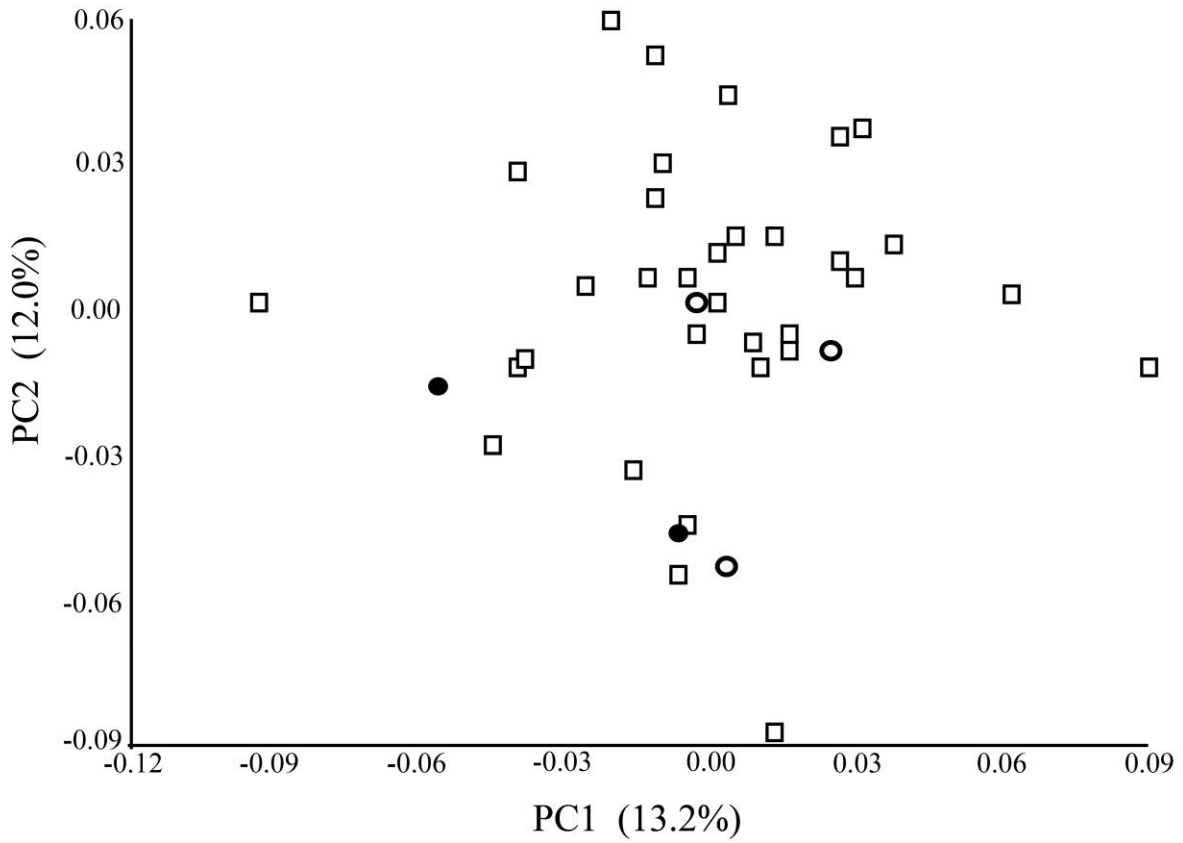
Figure S1) PCA chart displaying shape variance of female left distal humeri on PC1 and PC2,, representing 25.2% of the total shape variance. Open squares represent healthy joints, open circles are osteoarthritic joints, and filled circles are eburnated joints.

Table 1) Number of individuals analysed for each skeletal collection, with number of males and females summarized. Age and sex of skeletons were determined using standard osteological methods using cranial, mandibular, and pelvic morphology (Phenice 1969; Acsadi & Nemeskeri 1970; Lovejoy et al. 1985; Işcan et al. 1984, 1985; Brooks & Suchey 1990; Milner 1992).

Site	Period	Reference	♀	♂	YA	MA	OA	Total
Hereford Cathedral, Cathedral Close, Hereford, Herefordshire	Late medieval (7th-15th C)	Weston et al, *in prep*;	29	27	26	10	20	**56**
St James and St Mary Magdalene, Chichester, Sussex	Late medieval (12th-16th C)	Magilton et al 2008	19	47	20	17	29	**66**
Baldock, Hertfordshire	Romano-British (4th C)	Roberts 1984a,1984b	7	11	9	4	5	**18**
Hickleton, South Yorkshire	Late/ Post-medieval (11th -19th C)	Sydes 1984, Stroud *unpublished*	3	4	4	1	2	**7**
		Total	**58**	**89**	**59**	**32**	**56**	**147**

Table 2) Number of joints for each side and sex in groups labeled as eburnated, osteoarthritis (including those from the eburnation group), and healthy controls. Number of joints per individual studied was dependent on joint preservation.

		Eburnated		Osteoarthritis		Healthy		**Total**	
		♀	♂	♀	♂	♀	♂		
Ulnae	Left	2	8	8	16	20	31	**75**	
	Right	0	11	7	15	20	28	**80**	**155**
Humeri	Left	2	6	5	15	32	46	**98**	
	Right	3	8	10	21	27	44	**102**	**200**
Femora	Left	0	2	4	11	17	21	**53**	
	Right	3	3	7	14	12	19	**52**	**105**

Table 3) Summary of cross-validated DFA scores for non-pathological influences on shape on all three joints analysed. The DFA score indicates the percentage of joints accurately classified based on side, sex, and age.

| | Asymmetry | Sexual Dimorphism | | Age |
		Left	Right	
Ulnae	80.4%	70.8%	49.2%	39.8%
Humeri	73.9%	70.0%	73.9%	38.3%
Femora	89.9%	74.5%	72.9%	30.4%

Table 4) Crude prevalence rates (in percentage) of individuals and joints with eburnated joints and/or joints with osteoarthritis. Crude prevalence rate represents the number of individuals affected with the appropriate bones preserved.

	♀	♂	YA	MA	OA	Ulnae	Humeri	Femora
Eburnated	25.8%	12.1%	10.7%	21.9%	27.1%	15.5%	12.2%	9.7%
Osteoarthritis	42.7%	37.9%	28.6%	34.4%	59.2%	41.8%	27.5%	34.7%

Table 5) Cross-validated DFA scores of joints with eburnation compared to healthy joints for all three joints separated by side and sex. Scores are based on PCs which represent more than five percent of the total shape variance (up to PC8) and indicate the percentage of joints accurately classified as healthy or pathological.

		Male		Female	
		Left	Right	Left	Right
Ulnae	Eburnated	12.5%	36.4%	50.0%	-
	Healthy	61.3%	71.4%	90.0%	-
	Total	51.3%	61.5%	86.4%	-
Humeri	Eburnated	33.3%	50.0%	100.0%	33.3%
	Healthy	47.8%	72.7%	87.5%	77.8%
	Total	46.1%	69.2%	88.2%	73.3%
Femora	Eburnated	70.0%	100.0%	-	100.0%
	Healthy	90.5%	94.7%	-	100.0%
	Total	82.6%	95.5%	-	100.0%

Table 6) Cross-validated DFA scores of log centroid regressed variables of all joints with osteoarthritis (including eburnation) and healthy joints for all three joints separated by side and sex. Scores are based on PCs which represent more than five percent of the total shape variance (up to PC8) and indicate the percentage of joints accurately classified as healthy or pathological.

		Male		Female	
		Left	Right	Left	Right
Ulnae	Osteoarthritic	33.3.%	40.0%	37.5%	42.8%
	Healthy	41.4%	46.4%	70.0%	80.0%
	Total	38.3%	43.4%	60.7%	70.4%
Humeri	Osteoarthritic	66.7%	40.9%	80.0%	33.3%
	Healthy	82.6%	55.8%	71.8%	64.3%
	Total	78.7%	50.8%	72.9%	56.7%
Femora	Osteoarthritic	54.5%	64.3%	75.0%	71.4%
	Healthy	80.9%	78.9%	100.0%	75.0%
	Total	80.9%	72.7%	95.2%	73.7%