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EXTENDED REPORTS

The shape of the distal femur: a palaeopathological comparison of eburnated and non-eburnated femora

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Abstract

***Objectives*—To determine the difference in shape of the distal femur, viewed axially in two dimensions, between eburnated and non-eburnated femora.**

***Methods*—A comparison of 52 non-eburnated and 16 eburnated femora drawn from a large archeological skeletal population. Eburnation was taken to indicate late stage osteoarthritis. Shape variability, based on landmarks, was quantified using a principal components analysis after a Procrustes alignment.**

***Results*—A statistically significant difference was found between the two groups. This was with respect to the patellar groove and the shape of the medial condyle. The latter difference is consistent with bone remodelling as a knee stabilising mechanism.**

***Conclusions*—Anatomical shape can be quantified using an uncomplicated statistical technique. It was used to quantify the shape of the distal femur and demonstrate shape differences associated with osteoarthritis of the knee.**

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Osteoarthritis (OA) of the knee is a common, painful, and debilitating disease. About one in three people over the age of 65 years has radiological evidence of osteoarthritic changes at the knee.[1 2] Characteristic changes include cartilage degradation, subchondral sclerosis, and osteophyte formation around the margin of the articular surface.

The aetiology of OA is poorly understood. Dieppe and Kirwan[3] suggest a multifactorial model of OA aetiology. In this model, factors such as age, race, and sex, together with other systemic factors, such as hormonal status, influence a person's susceptibility to OA, but it is local joint biomechanics (including joint shape) that determine the occurrence and severity of OA at different joint sites.

The biomechanics of the knee joint have been studied comprehensively in relation to OA aetiology and treatment.[4 5] Some factors that have been investigated include obesity,[6–8] trauma,[9] lower limb malalignment,[10–13] and mechanical instability.[14 15]

The relation between joint shape and OA has not been fully elucidated and few empirical data exist. It is well accepted that an alteration in joint shape occurs as a result of OA. Indeed, one feature of the original Kellgren and Lawrence scoring system was an alteration in bony contours.[16] It has also been hypothesised that joint shape, influencing joint biomechanics, could increase the risk of OA. Johnson suggested that bone remodelling, altering joint shape, had a role in the aetiology of OA[17] as has Bullough.[18] Yoshioka *et al*[19] have studied the shape of the distal femur and noted a large natural variation in shapes that could be involved in the genesis of knee OA. More recently, Cook *et al*[20] have presented evidence that varus and valgus deformities can result from the shape of the distal femur and proximal tibia that precede any osteoarthritic change and have suggested that such deformities may be risk factors for knee OA. It has also been suggested that bone remodelling may be a response to OA in an attempt at joint repair and stabilisation forming a "negative feedback" that could slow the progress of OA.[21] This is supported by the observation that marginal osteophytes decrease varus-valgus instabilities[22] and may also decrease anterior-posterior translation.[23]

The shape of the distal femur may, therefore, be very pertinent in the aetiology of knee OA. To the best of our knowledge, a quantitative analysis of the shape of the distal femur (rather than an analysis of individual morphological measurements) has not been conducted with respect to knee OA. Such an analysis might characterise differences in shape that may precede, and therefore be risk factors for, OA.

We have examined femora from a large archeological population and used appropriate techniques to represent their shape in a format suitable for statistical analysis. Skeletal material lends itself well to the examination and recording of bony changes associated with OA.[24] Eburnation, a "polished" area of articular surface, is considered unequivocal evidence of full depth loss of cartilage.[25] The shape of the distal end of the femur (viewed axially) was extracted using a landmark based approach. A group of

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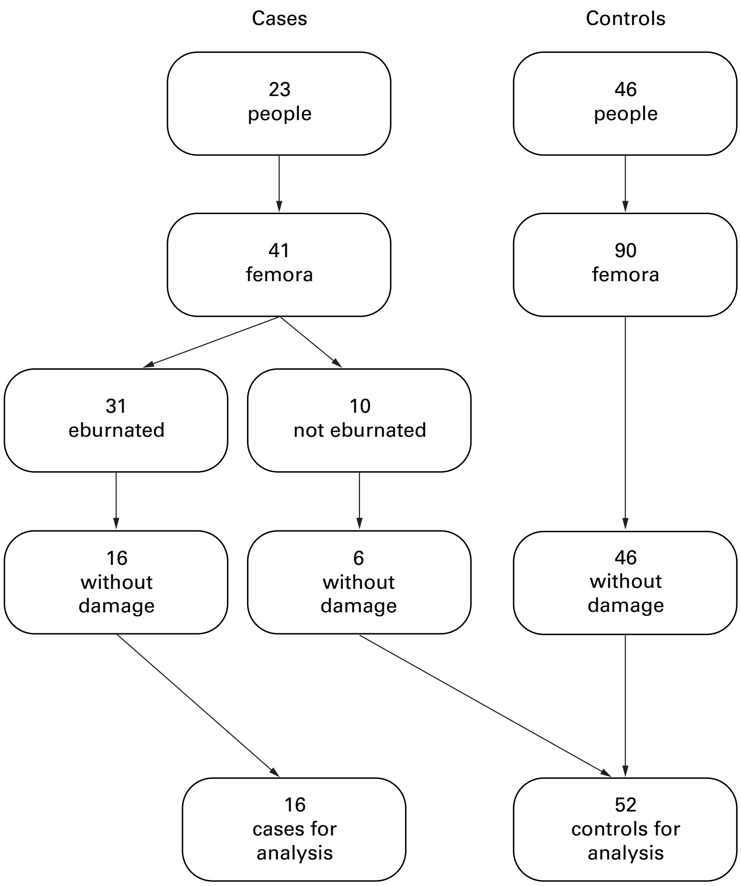

Figure 1 Illustration of selection of study material.

eburnated femora was compared with a non-eburnated group.

Methods

The study material consisted of a sample of adult femora taken from a large skeletal collection excavated from St Peter's Church, Barton on Humber, in the north of England. Approximately 2000 adults were available for study. The presence of eburnation (indicating a site of complete cartilage loss) anywhere on the distal articular surface of the femur was considered indicative of knee OA. The presence of osteophytes alone was considered insufficient for the diagnosis of OA. An attempt was made to identify every person with eburnation and seek, for each, two age and sex matched controls. Standard anthropological techniques were used for age and sex determination.[26]

Twenty three people had distal eburnation on at least one femur. A pool of people with no evidence of OA, at any site, was identified. From this pool, 46 persons were selected as controls. Because of missing femora, this selection resulted in 31 eburnated femora and 90 non-eburnated femora. Femora with postmortem damage were later discarded. The number of femora used is given in the results and shown in figure 1.

DATA CAPTURE

The distal end of each femur, viewed axially, was filmed using a video camera as indicated in figure 2. The camera was fixed upon a horizontal surface. The femora were placed on this surface and allowed to rest naturally upon the posterior aspects of the femoral condyles at the distal end and the greater trochanter at the proximal end. The distance between the camera lens and each femur was 30 cm. Each femur was rotated in the horizontal plane until the articular surface was parallel with the plane of the camera lens.

A bitmap image of each articular surface was created by digitising the video film. This was converted to a simple black and white bitmap showing the outline of the bone. Figure 3 shows an example. All left femora were reflected to produce "right" images so that the left side of any image indicates the lateral side and the right side the medial.

Six landmarks were initially defined. The terms "low" and "high" are used with reference to the position of a point within a bitmap image rather than a point on a bone; for example, a "low" point is in fact a posterior point. The landmarks selected were the "lowest" point of the patellar grove; the two "highest" points of the patellar groove; the "highest" point of the intercondylar notch and the two "lowest" points of the condyles.

Further landmarks were then defined as follows. A line was used to join the highest and lowest lateral points (points 12 and 9). A perpendicular bisector was then extended from this line to the edge of the bone. The point at which the perpendicular bisector crossed the

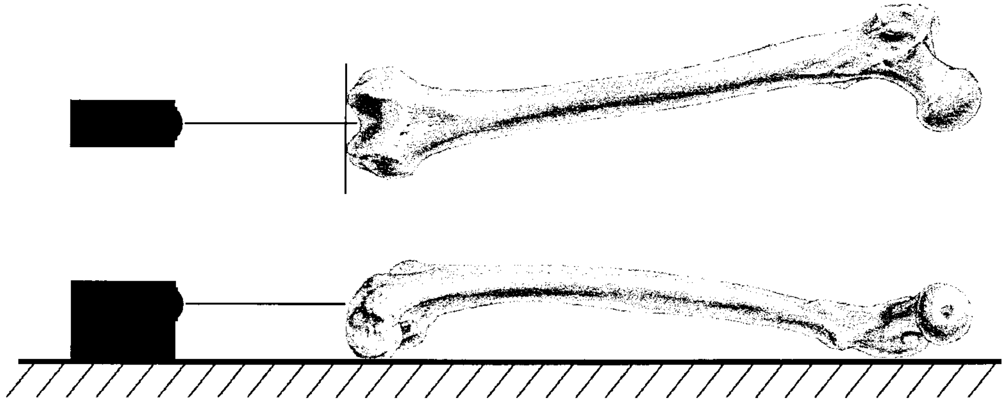

Figure 2 Alignment of femora to camera: femora are allowed to rest naturally upon the trochanters and most posterior points of the condyles.

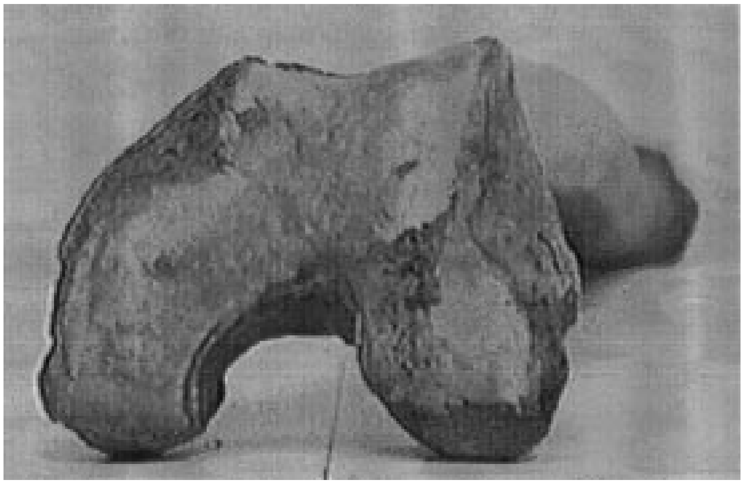

Figure 3 Example of bitmap digitised from video image.

edge of the bone was defined as another landmark (point 11). A line was then used to join this new landmark to the lowest lateral point. Again, a perpendicular bisector to this new line was extended to the edge of the bone and a new landmark located (point 10). An identical procedure was carried out on the medial side to create two new landmarks (points 3 and 4). A new landmark was created on the lateral (and medial) side of the intercondylar notch using the same process. A line was used to join the lowest lateral (medial) point and the highest point of the intercondylar notch (point 7). Perpendicular bisectors of these lines were then extended to the edges of the intercondylar notch and new landmarks defined (points 6 and 8). Figure 4 shows the location of the 12 landmarks, labelled 1 to 12. We felt that the presence of eburnation would have a very minor physical effect, if any, upon the location of any of these landmarks. Therefore we do not believe that eburnation, in itself, could alter the shape of the distal femur as defined here.

The coordinates in two dimensions of the 12 landmarks were read using image viewing software. The shape of each bone, therefore, was represented as a configuration of 12 points quantified as 24 variables—that is, an "x" coordinate and a "y" coordinate from each landmark.

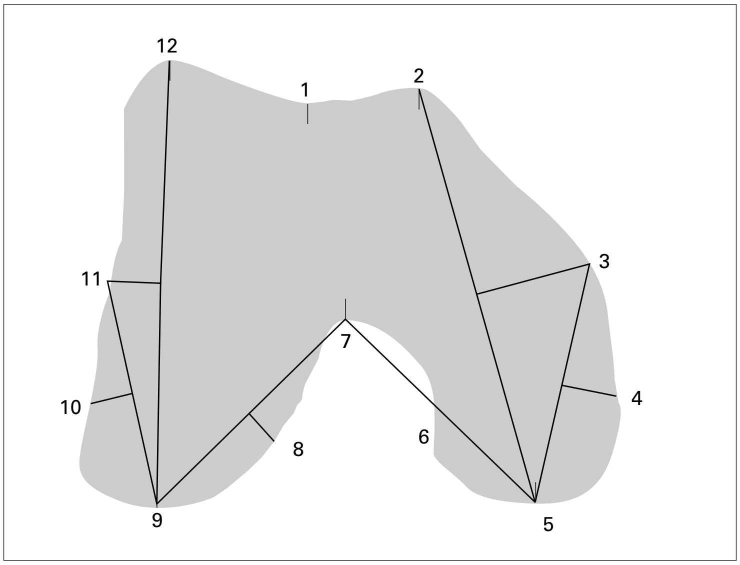

Figure 4 Location of 12 landmarks used for analysis. Landmarks 1, 2, 5, 7, 9, and 12 were located by hand. The remaining six landmarks were defined relative to these.

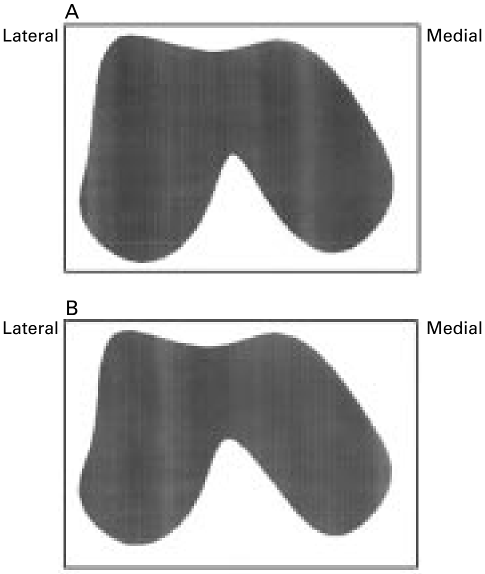

Figure 5 Mean configurations. Periodic splines were used to produce outlines for the 12 landmark mean configurations. The mean shape of the 16 eburnated femora is shown (A) compared with that of the 52 non-eburnated (B).

A study was done to assess the reproducibility of the configuration of landmarks. Twelve bones were selected at random. The landmarks for these specimens were then identified and recorded on two separate occasions 24 hours apart. An intra-class correlation coefficient was calculated based on these repeated measurements.

STATISTICAL METHODS

The aim of the analysis was to provide a simple quantification of shape variation, independent of overall size, thereby facilitating a quantitative comparison between groups of femora. To remove variability between the configurations because of overall size, orientation, and position within an image the configurations of points were preprocessed using a generalised Procrustes fitting procedure.[27] Each configuration is centred at its centre of gravity (that is, the middle point of the configuration), rotated about that point, and scaled until the overall total difference between configurations is minimised.

The mean configuration for each group was straightforward to calculate. After the Procrustes fitting, the mean of each of the 24 variables comprising the coordinates of the 12 landmarks was calculated. The mean configuration is the configuration produced form these mean coordinates.

Quantification of the variation between configurations is not so straightforward. Simply looking at the variability in the location of the 12 landmarks individually ignores the covariance (or joint variability) between them. A principal components analysis was applied to

Table 1 Comparison of first five principal component scores between eburnated and non-eburnated femora

Component	*% of total variance*	*Non-eburnated (n=52) mean (SD)*	*Eburnated (n=16) mean (SD)*	*t value*	*p value*
1st	21	−0.0019 (0.036)	0.0063 (0.030)	-0.83	0.409
2nd	18	−0.0062 (0.031)	0.0202 (0.029)	-3.01	0.004
3rd	12	0.0020 (0.023)	−0.0064 (0.037)	0.860*	0.401*
4th	9	0.0015 (0.023)	−0.0048 (0.023)	0.94	0.348
5th	8	−0.0014 (0.021)	0.0047 (0.022)	1.00	0.321

* Resulting from an unpooled *t* test.

Table 2 Comparison of first five varimax rotated component scores between eburnated and non-eburnated femora

Component	*% of total variance*	*Non-eburnated (n=52) mean (SD)*	*Eburnated (n=16) mean (SD)*	*t value*	*p value*
1st	11	0.0030(0.021)	−0.0098(0.036)	1.37*	0.189*
2nd	14	−0.0040(0.028)	0.0131(0.025)	−2.17	0.033
3rd	15	−0.0043(0.029)	0.0141(0.028)	−2.24	0.029
4th	13	−0.0008(0.028)	0.0028(0.028)	−0.46	0.648
5th	16	−0.0023(0.031)	0.0076(0.026)	−1.16	0.250

* Resulting from an unpooled *t* test.

the coordinates of the aligned landmarks. The extracted components identify important modes of joint variability in landmark locations—that is, ways in which the configuration varies as a whole. This analysis follows that suggested by Cootes *et al*.[28] Each important mode of shape variability—that is, each principal component—can be thought of as a shape variable with a particular value corresponding to a particular shape. The variance of each of these variables accounts for a proportion of the total variance in the sample. Each shape variable can be visualised by plotting the shape corresponding to extreme values of each variable (that is, the mean value plus and minus 3 standard deviations). To aid visualisation, a smooth outline of each configuration displayed was interpolated using a periodic spline.[29] Two sample *t* tests were then applied to these shape variables to test for between group differences in shape. Statistical significance was set at the 5% level.

A varimax rotation[30] was applied to aid interpretation of each mode of shape variability. A varimax rotation expresses the variability covered by the principal components but in an alternative fashion. It attempts to produce components that express joint variability of landmark location restricted to a small number of landmarks.

Results

Because of postmortem damage, only 68 femora were available for analysis. Of these 16 had eburnation. These came from three people with bilateral disease and 10 with unilateral disease. A total of 52 femora without eburnation was available. This group included six contralateral femora from the 10 people with unilateral eburnation. Figure 1 indicates this selection process.

Lone eburnation of the patellofemoral compartment was evident in 13 femora (3 medial and 10 lateral) and two femora had lone medial tibiofemoral eburnation. One femur had eburnation of both the medial patellofemoral and tibiofemoral compartments.

Osteophytes were evident on all eburnated femora and 44 (85%) of the non-eburnated femora. The eburnated femora tended to have larger and more widespread osteophytes than the non-eburnated femora. The osteophytes in the non-eburnated group were often very small and occurred only within the intercondylar notch region. Many of the eburnated femora showed signs of pitting on the articular surface, which was never present in the non-eburnated group. None of the eburnated femora showed any signs of erosions that would be suggestive of rheumatoid arthritis.

Two femora from the control group came from people that could not be sexed. Of the remaining controls, 23 (46%) femora came from men and 27 (54%) came from women. This distribution was similar to that of the eburnation group: seven (44%) coming from men and nine (56%) from women. Age could not be determined in people for 16 femora, nine from the eburnation group and seven from the control group. All of the remaining eburnated femora (7) came from people aged 45 years or over. Of the remaining control femora, six (13%) came from people aged less than 45 years and 39 (87%) came from people aged 45 years or over.

The intra-class correlation coefficient resulting from the reproducibility study was 0.806 indicating a moderate to high degree of reproducibility for the overall configuration.

The mean configurations, outlined using periodic splines, for both eburnated and non-eburnated groups are shown in figures 5 (A) and 5 (B).

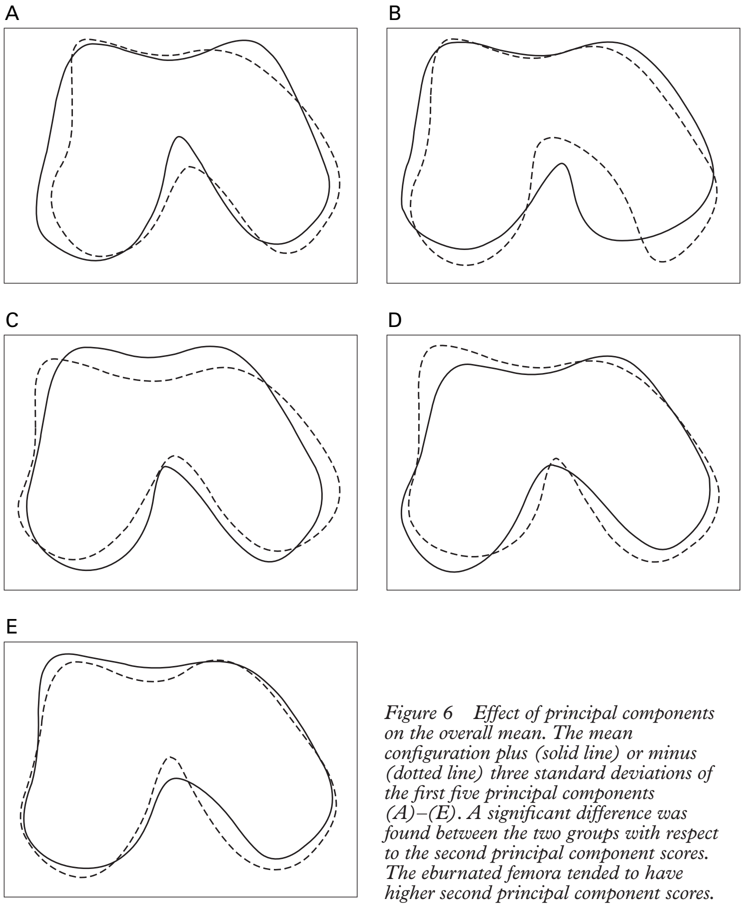

Figure 6 Effect of principal components on the overall mean. The mean configuration plus (solid line) or minus (dotted line) three standard deviations of the first five principal components (A)–(E). A significant difference was found between the two groups with respect to the second principal component scores. The eburnated femora tended to have higher second principal component scores.

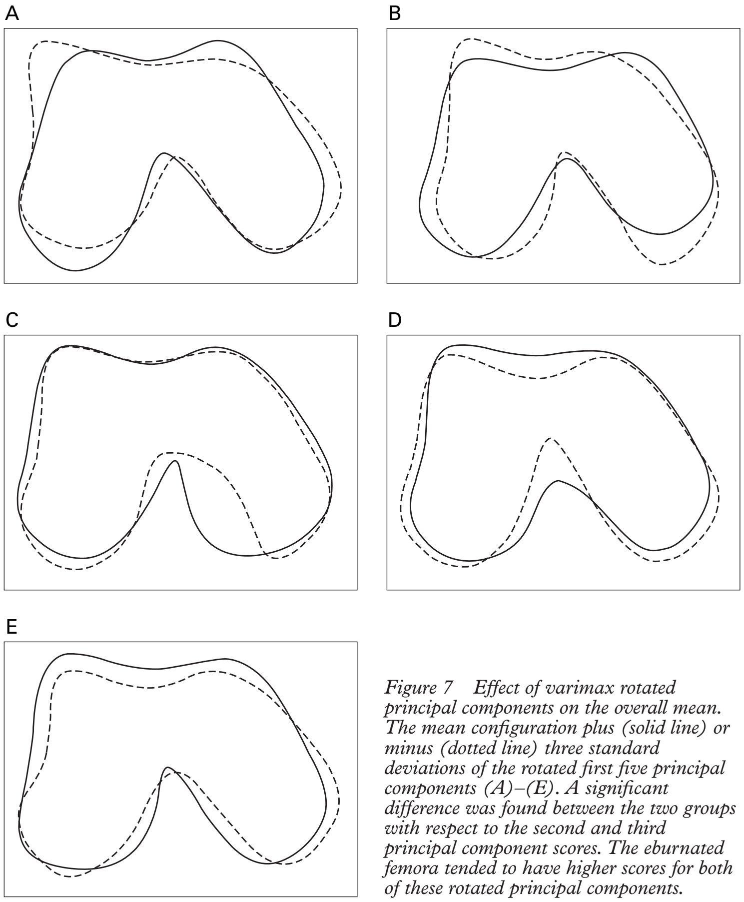

Figure 7 Effect of varimax rotated principal components on the overall mean. The mean configuration plus (solid line) or minus (dotted line) three standard deviations of the rotated first five principal components (A)–(E). A significant difference was found between the two groups with respect to the second and third principal component scores. The eburnated femora tended to have higher scores for both of these rotated principal components.

The first five principal components accounted for over 68% of the total sample variation (table 1). The modes of shape variability captured by these components are presented in figures 6 (A) to 6 (E) where the mean configuration plus and minus 3 standard deviations of each principal component have been plotted. A varimax rotation was applied to these first five principal components. The individual contributions to the total variation explained by these rotated components are shown in table 2. The shape variability of these are presented in figures 7 (A) to 7 (E).

A significant mean difference between eburnated and non-eburnated femora was found for the second principal component. The eburnated group had a higher mean score implying relatively broader condyles (especially the medial condyle), a narrower intercondylar notch with a more medial rather than lateral, anterior twist, a straighter, less concave, lateral edge to the lateral condyle and a more symmetric patellar groove (see fig 6 (B)).

There was a significant difference between the eburnated and non-eburnated mean scores for the second and third varimax rotated components. The second rotated component captures variability in the patellar groove (also seen for the second principal component); eburnated femora have a shallower, more symmetric patellar grove (see fig 7 (B)). The third rotated component reflects differences in the intercondylar notch and the lateral edge of the lateral condyle (these are also aspects of the second principal component). Eburnated femora have a narrower intercondylar notch with a more medial anterior twist (see fig 7 C). The lateral condyle appears straighter. Thus the second and third varimax rotated components capture the same shape variability as the second principal component but focus on particular regions of the femur.

The component scores were compared with respect to the location of eburnation (either at the tibiofemoral region or the patellofemoral region). These results are presented in tables 3 and 4. The shape differences compared with non-eburnated femora with respect to the second principal component and third rotated component appear to be greater for the tibiofemoral group than for the patellofemoral group. This is not so for the second rotated component where the tibiofemoral eburnated and patellofemoral eburnated bones had a similar mean score. However, the small number of femora with tibiofemoral region eburnation precluded any formal analysis.

Table 3 Comparison of first five principal component scores between eburnated and non-eburnated femora: eburnation group split by location of eburnation

Component	*% of total variance*	*Non-eburnated (n=52) mean (SD)*	*Tibiofemoral eburnation (n=3‡) mean (SD)*	*Patellofemoral eburnation (n=13) mean (SD)*	*t value†*	*p value*
1st	21	−0.0019 (0.036)	0.0067 (0.026)	0.0063 (0.032)	−0.75	0.457
2nd	18	−0.0062 (0.031)	0.0384 (0.035)	0.0160 (0.027)	−2.35	0.022
3rd	12	0.0020 (0.023)	−0.0243 (0.038)	−0.0023 (0.037)	0.516*	0.608*
4th	9	0.0015 (0.023)	−0.0188 (0.022)	−0.0016 (0.023)	0.426	0.671
5th	8	−0.0014 (0.021)	−0.0090 (0.034)	0.0079 (0.019)	−1.44	0.155

* Resulting from an unpooled *t* test. † Resulting from a comparison of non-eburnated femora with patellofemoral eburnated femora.
† Including one femur with tibiofemoral and patellofemoral eburnation.

Table 4 Comparison of first five varimax rotated component scores between eburnated and non-eburnated femora: eburnation group split by location of eburnation

Component	*% of total variance*	*Non-eburnated (n=52) mean (SD)*	*Tibiofemoral eburnation (n=3‡) mean (SD)*	*Patellofemoral eburnation (n=13) mean (SD)*	*t value†*	*p value*
1st	11	0.0030 (0.021)	−0.0267 (0.037)	−0.0059 (0.036)	0.86*	0.403*
2nd	14	−0.0040 (0.028)	0.0173 (0.019)	0.0122 (0.027)	−1.86	0.067
3rd	15	−0.0043 (0.029)	0.0376 (0.047)	0.0087 (0.021)	−1.51	0.135
4th	13	−0.0008 (0.028)	−0.0104 (0.017)	0.0058 (0.029)	−0.77	0.445
5th	16	−0.0023 (0.031)	0.0042 (0.027)	0.0084 (0.027)	−1.14	0.257

* Resulting from an unpooled *t* test. † Resulting from a comparison of non-eburnated femora with patellofemoral eburnated femora.
† Including one femur with tibiofemoral and patellofemoral eburnation.

The component scores of the six contralateral femora from people with unilateral eburnation were examined but no clear pattern emerged. Small numbers again precluded formal statistical analyses.

There were no statistically significant (or near statistically significant) differences for men and women with respect to any of the first five principal component scores or varimax rotated scores.

Discussion

This study provides evidence of a difference in shape between femora with and without full thickness loss of cartilage (that is, eburnation) at the distal end in a sample derived from a large skeletal population. We have considered eburnation to indicate the presence of OA and suggest that we have illustrated shape differences associated with OA of the knee. We do not believe that this shape difference could be attributable to eburnation, in itself.

It is probable that some of the non-eburnated femora were in fact osteoarthritic, particularly as contralateral non-eburnated femora were included in the control group. The bias introduced into the study from this misclassification will reduce any difference between the eburnated and non-eburnated groups. Thus, the difference we observed was probably an underestimate but was, nevertheless, large enough to be statistically significant.

It is unlikely that the observed differences are a result of a confounding factor. The age and sex distributions of the eburnated and non-eburnated groups were very similar. There was, however, a large number of eburnated femora that were unaged, which could have meant a disparity in ages that went unobserved. For this to be so, the majority of unaged eburnated femora would have to be under 45 years. This is highly unlikely given the known age distribution of the onset of OA. A larger number of eburnated femora compared with non-eburnated femora could not be used in this analysis because of postmortem damage. For this to cause a bias there would need to be an association between postmortem damage (usually sustained during archeological excavation) and distal femoral shape. This seems highly unlikely.

We know of no previous study that has investigated knee OA with respect to overall distal femoral shape. The width of the intercondylar notch has been considered, for example, by Good *et al*,[31] who concluded that damage to the anterior cruciate ligament was related to a narrow intercondylar notch. The congruence angle of the patella has also been investigated, for example by Harrison *et al*,[10] who found that a lack of congruence was related to patellofemoral OA.

A difference was found between eburnated and non-eburnated femora with respect to the shape of the condyles. The eburnated femora, on average, tended to have wider medial condyles than the non-eburnated. This is consistent with bone remodelling in response to a change in biomechanics, such as a varus deformity. An increase in medial condyle surface area would help stabilise an unstable joint or dissipate an increased pressure through the condyle. Such a change in biomechanics may either precede or result from loss of cartilage. These data, thus, support the concept of a "negative feedback" in which reshaping of joints is an attempt to slow, or counter, the OA process.[21] Rogers *et al*[32] have shown a wide variation in ability of people to form bone and have speculated that those people with a greater tendency to form bone in response to some stress, labelled "boneformers", may progress differently with regard to OA.

This condyle shape difference appeared more characteristic of the tibiofemoral than the patellofemoral eburnated femora. These findings were based on only three femora with tibiofemoral disease and no conclusions should be drawn. However, it is conceivable that bone remodelling in OA differs with regard to location as different local biomechanics are associated with different localities. This idea has been discussed[33] and it has already been suggested from an epidemiological study[34] that the risk factors for knee OA differ between compartments.

The difference in condyles may account for the shape and width differences of the intercondylar notch. The eburnated group seemed to have narrower notches that twisted more medially than laterally. However, it is conceivable that differences in intercondylar notch shape could change the functioning of the cruciate ligaments, or increase the likelihood of damage, and lead to an increased risk of knee OA.

The patellar groove appeared to be shallower in the eburnated group with a relatively lower lateral edge. It is possible that the difference results from the development of osteophytes on the medial joint margin, increasing both the height of the medial edge and the width of the groove. Interestingly, a postmortem study of the knee[35] found considerable variation in the shape of the patellar groove; in some specimens it was practically absent. A naturally occurring wide variation in patellar groove shapes suggest this could be a potential risk factor, with a shallow patellar groove leading to subluxation and then OA of the patellofemoral joint.

From this initial cross sectional exploration it cannot be concluded that any of the observed differences in shape are risk factors for knee OA. However, a longitudinal, clinical study would provide the opportunity to test the hypothesis that one, or both, of these observed variations in joint shape is a risk factor for OA. Magnetic resonance imaging could be used to provide non-invasive information on joint shape in three dimensions. It would not be difficult to extend the techniques used here (and other shape analysis techniques) to the analysis of magnetic resonance imaging.

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