

Trabecular angle of the human talus is associated with the level of cartilage degeneration

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Abstract

The architecture of bone trabeculae is based on the direction of stresses applied to the bone. The human talar dome receives compressive forces from the tibia and, to a much lesser extent, the fibula when standing, walking, and running, and transmits the force downward to the calcaneus through the talar body and anterior to the navicular via the talar head. As a result, the body of the talus has predominately vertical trabeculae. However, here we hypothesize that cartilage degeneration at the articular surface is associated with trabecular angle within the associated bone, as a reflection of joint alignment and/or biomechanics (stability, congruence, angulation, etc). Through measurement of trabecular angle with Fast Fourier Transform Analysis, we show a positive correlation between the cartilage degeneration score of the articular surface of the talar dome and the angle of trabecular deviation from the perpendicular axis of the dome (right talus $R=0.75, p<0.01$; left talus $R=0.79, p<0.01$).

Keywords: Talus, Trabeculae, Osteoarthritis, Bone, Fast Fourier Transform

Introduction

The architecture of cancellous bone is based on its mechanical demands, as described by Wolff's Law. Specifically, the trabecular patterns of a bone are formed by the stress trajectories that are placed on that bone¹. The preferred directional orientation of the trabeculae thus provides a history of the stresses to which the bone has been subjected². The trabecular patterns of several bones, in relation to their stresses, have already been described in detail, including the talus, calcaneus, hip, vertebrae, and the distal radius³. However, this trabecular alignment has not previously been investigated as it relates to the integrity of the joint surfaces through which these stresses pass.

The trochlea of the human talus receives compressive forces from the tibia and fibula⁴⁻⁶ when standing, walking, and running, and transmits the force to the calcaneus through the

talar body, and anteriorly to the navicular via the talar head. As a result, the body of the talus has predominately vertical trabeculae, running superiorly to inferiorly². However, it is well known that a change in alignment and/or biomechanical function at a joint, such as in joint stability, congruence, anatomical angulation, etc., changes the contact characteristics and loading of the opposing articular surfaces, leading to cartilage degeneration and osteoarthritis⁷⁻⁹. Thus, here we hypothesize that cartilage degeneration at the articular surface is associated with trabecular angle within the associated bone, as a possible reflection of alignment and/or biomechanics at the joint. In the present study we show a positive correlation between the cartilage degeneration score at the articular surface of the talar dome and the angle of trabecular deviation from the perpendicular axis of the dome.

Methods

Specimens and radiography

The study specimens consisted of thirty-eight intact human tali from 20 donors with an age range of 41-84 years and a mean age of 70.5 years. All specimens were received from the Gift of Hope Organ and Tissue Donor Network of Illinois, with approval of the Institutional Review Board of Rush University

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Medical Center, within 24 hours of death. Each talus was separately graded by two osteoarthritis investigators to determine the level of cartilage degeneration. The tali were graded on the five point modified Collins scale¹⁰ with grade 0= normal cartilage appearance with no signs of degeneration; grade 1= surface fibrillation; grade 2= ulceration and/or fissuring or focal loss of the upper layers of cartilage; grade 3=30% or less of the articular surface eroded down to the subchondral bone (Figure 1). Because there were no tali displaying more than 30% of the articular cartilage eroded down to the subchondral bone, Grade 4 tali were not included in the study. The exact location of the cartilage damage on each talus was noted.

The head of each talus was removed with a saw, so that a full, unobstructed view of the talar dome trabeculae could be seen in radiographs of the specimens. Great care was taken to position each talus exactly perpendicular with respect to the X-ray beam and so that each talus was positioned with its horizontal axis exactly parallel to the stage on which the specimen was seated. A posterior-anterior (P-A) contact X-ray was taken of each talar dome. Each radiograph was taken at 90 kvp for 18 seconds and then digitized using an Epson Expression 1680 scanner using the following settings: 16-bit Gray (HiFi) for Image Type, TPU for positive film for the document source, and a resolution of 300. Each radiograph was set to a standard size of approximately 650 x 500 pixels using Adobe Photoshop 6.0 and subsequently converted to a Windows Bitmap file.

Fast Fourier Transform

A third investigator blinded to the cartilage grades performed a Fast Fourier Transform (FFT) analysis for each digitized X-ray. The FFT analysis has previously been used to describe the trabecular orientation and anisotropy of radiographic images of bone and soft tissue¹¹. The software first rescales the gray levels of the selected ROI on the radiograph, and then determines the directionality of the selected field by using a power spectrum to generate an intensity histogram to show the distribution of the angles within a given region of interest. The power spectrum is generated using segments that correspond to increments of one degree of orientation¹². The FFT analysis does not allow analysis of individual trabeculae, but instead examines the entire pattern of trabecular orientation within a region of interest¹².

The details of the FFT program are as follows. Briefly, the gray level of each pixel of the image was represented by a function, $g(x,y)$, where x and y are the Cartesian co-ordinates of a pixel point. The two-dimensional discrete Fourier transform of $g(x,y)$ is written $F(n,m)$ and described as:

$$F(n,m) = \frac{1}{N^2} \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} g(x,y) \exp\{-2\pi i(xn + ym)/N\},$$

where n and m are spatial frequency corresponding to x -axis and y -axis of the original image, respectively. The value for N is the size of a two-dimensional square array and should be the power of 2 ($N=128$ in this study).

The preferred orientation in the original image is repre-

sented by a peak in the power spectrum $|F(n,m)|^2$ around the origin of the frequency transforms.

In order to quantitate the orientation, the summation of the power spectrum within a narrow fan shaped area was calculated. For this purpose, the power spectrum, $|F(n,m)|^2$ was transformed from the Cartesian system to a polar system, $|P(r,\theta)|^2$. Then, the function $P(r,\theta)$ was decomposed into $p_\theta(r)$ for each θ , and $p_r(\theta)$ for each r yielding a pair of function $[p_\theta(r), p_r(\theta)]$ to be used by the texture operator. The intensity of the orientation in an angle of θ , $F(\theta)$, was indicated by summation of the power spectrum within a fan shaped area, and written as:

$$F(\theta) = \sum_{r=a}^b p_\theta(r),$$

where a is a lower cut off level ($a=6$) and b is a higher cut off level ($b=128$) of a band-pass filter¹².

The distribution function, $f(\theta)$, was calculated as:

$$f(\theta) = \frac{F(\theta)}{\sum_{\theta=1}^{180} F(\theta)}$$

The trabecular angle was defined as the angle at which the value of distribution function was highest. All analyses, including the two-dimensional FFT, polar transformation, and calculation of the distribution function, were performed with custom Window-based interactive software program written in Visual C++ .NET 2003 with Microsoft Foundation Class programming (Microsoft Corp, Redmond, WA)^{11,12}.

Medial and lateral regions of interest (ROI), each of 128 x 128 pixels, were established on each radiograph. The horizontal axis of each talus was first established at the superior aspect of the talar trochlea by drawing a line from the most superior border of the medial aspect of the trochlea to the most superior border of the lateral aspect of the trochlea. Care was taken for consistency in determining this line as it established the horizontal axis of each talus to which the perpendicular axis (mid-sagittal line) and, in turn, trabecular angle would be compared. The mid-sagittal line was established by drawing a line superior to inferior down the middle of the talus, and perpendicular to the line establishing the horizontal axis of the talus. ROIs were located in the center of these medial and lateral halves. The area of each ROI was 128 x 128 pixels, which is 1.19 cm x 1.19 cm. Trabecular angle was then measured in the medial and lateral ROIs with respect to the midsagittal line of each talus (Figure 2), through the FFT program described above. The mean of three separate measurements at different locations within each ROI was calculated. These measurements were determined to be either medially or laterally directed depending upon whether the angle was less than or greater than 90°, as determined by the FFT result. The midsagittal line in each talus was utilized as the 90 degree baseline angle (perpendicular to the horizontal axis of the talus). Thus, for right tali, angles less than 90° were directed toward the medial side and angles between 90° and 180° were directed laterally. Since the X-rays were taken from a P-A view, the opposite was true of the left tali samples whereby angles between 0° and 90° were directed laterally.

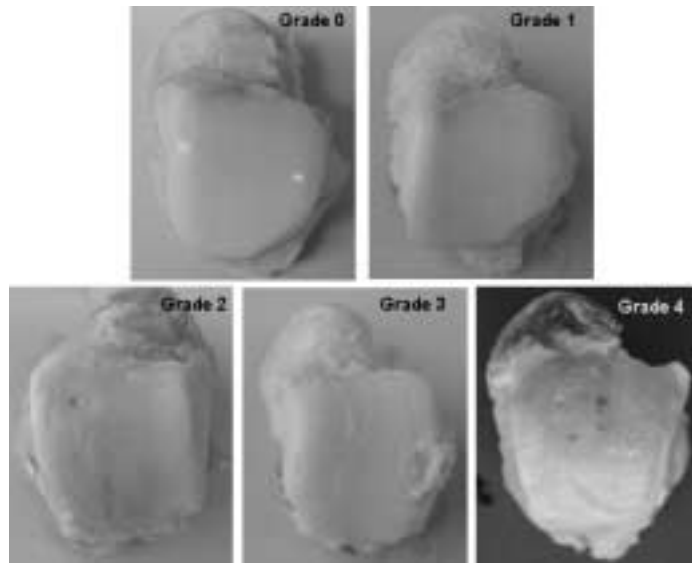


Figure 1. Gross morphological appearance of cartilage at different grades of degeneration. The modified Collins' scale is used to grade the amount of cartilage degeneration on the trochlea of each talus. A grade 0 talus is normal with no damage to the articular cartilage; a grade 1 talus shows fibrillations in the articular surface of the trochlea; a grade 2 cartilage shows ulcerations and/or fissuring in the upper surface of the articular cartilage; a grade 3 cartilage demonstrates erosion of the cartilage to the level of subchondral bone in less than 30% of the articular surface; and a grade 4 cartilage shows more than 30% of the articular cartilage eroded down to the level of subchondral bone.

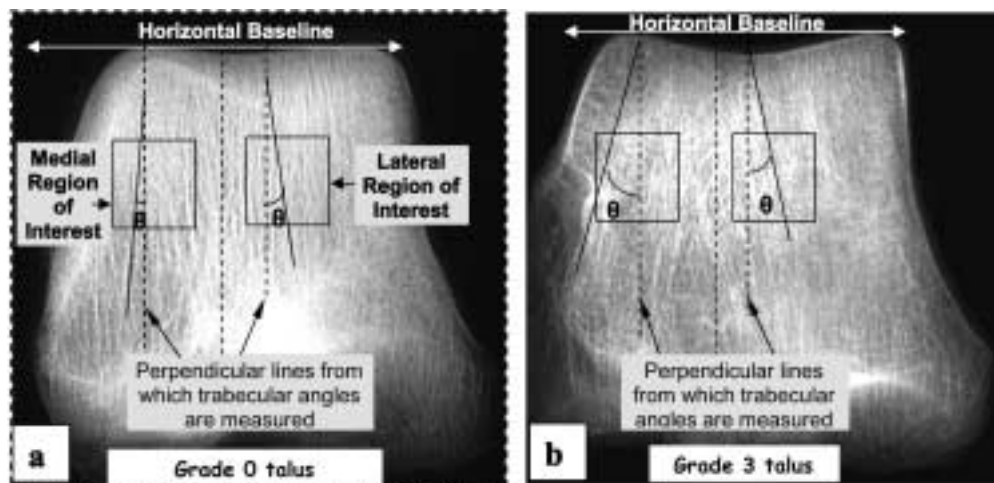


Figure 2. Regions of interest for fast Fourier transform. Examples of a grade 0 cartilage degeneration talus (a) and a grade 3 cartilage degeneration talus (b) demonstrating differences in the trabecular angles (θ) in relation to the perpendicular axis of the talus. As an example, it is apparent that the grade 0 talus displayed a smaller trabecular angle in both medial (3.3°) and lateral (6.7°) regions of interest as compared to those in (b) (19.7° and 13.7° , respectively). The solid black lines are superimposed over actual individual examples of trabeculae. The FFT analyses calculate the mean angle for all trabeculae within a given region of interest.

Statistical analyses

Statistics were performed using StatView Software. The nonparametric test, Spearman Rank Order Correlation, was used to determine the correlation between trabecular angle

and the following parameters: cartilage degeneration score, weight, and age. Correlation was also determined between age and cartilage degeneration score, and body weight and cartilage degeneration score. Correlation is reported as "R". Statistical significance was taken at $p < 0.05$.

Trabecular angle direction	Number of Donors (n=18)	Right tali	Left tali
Trabeculae of only one talus of a donor directed medially	NA	1	1
Trabeculae of only one talus of a donor directed laterally	NA	3	2
Trabeculae of only one talus directed medially in one ROI and laterally in the other ROI	NA	4	7
Trabeculae of <u>both tali</u> of a donor directed medially	0	NA	NA
Trabeculae of <u>both tali</u> of a donor directed laterally	9 (or two tali from each donor= 18 tali)	NA	NA
Talar trabeculae of both tali of a donor directed in opposite directions	1	NA	NA
ROIs in various directions	8	NA	NA

Table 1. A breakdown of the relationships between the trabecular angles within tali, and between tali within individual donors. The first three rows deal only with donors with unmatched pairs of tali in terms of trabecular patterns. The bottom four rows deal only with donors with pairs of tali with matching trabecular patterns. The numbers in **bold face** refer to those tali in which the trabeculae of both ROIs are directed laterally, which appears to be the most prominent condition considering all tali.

Results

A breakdown of the relationship of the trabecular angles in the two ROIs of individual tali, and in both tali within individual donors, can be seen in Table 1. Twenty-three tali of 14 donors (from a total of 38 tali of 20 donors) had trabeculae directed in the lateral direction in both the medial and lateral ROIs. In these tali, the angulation of the trabeculae ranged from 4.3° to 18.3° . Eight tali had trabeculae with an orientation in a combination of medial and lateral directions in the respective ROIs. Only two tali, each from a different donor, had trabeculae running medially in both ROIs. In these tali, the angulation of the trabecular ranged from 6.7° to 8.7° in the medial ROI and 5.3° to 10.3° in the lateral ROI. The standard deviation of the mean of three separate measurements at different locations within each ROI ranged from a high of 7.2 degrees to a low of 0 degrees, with a mean of 1.5 degrees.

The breakdown of cartilage scoring was as follows: 7 tali from 5 donors at grade 0 (normal, displaying no cartilage degeneration); 19 tali from 11 donors at grade 1, 9 tali from 6 donors at grade 2; and 3 tali from 3 donors at grade 3. The location of damage to the cartilage in the grade 1 tali was variable. Fibrillations could occur anywhere on the articular surface, with the majority occurring on the tibial plafond articular surface (the superior aspect of the trochlea). The grade 2 and the grade 3 tali displayed damage predominantly on the medial and lateral articular borders where, during motion, they rub against the margins of the tibia and fibula, respectively.

Concerning cartilage degeneration, it was found that the cartilage grade on the talar trochlea was positively correlated (right talus $R=0.74$, $p<0.01$; left talus $R=0.78$, $p<0.01$) with the angle of trabecular orientation for both tali of the donors, as can be seen in Figure 3. For these data, the medi-

al and lateral ROI values were averaged together. The tali of left and right ankles were plotted separately in Figure 3. There was also a strong correlation between cartilage degeneration and trabecular deviation in the medial and lateral ROIs when calculated separately (medial ROI: right talus $R=0.75$, $p<0.01$; left talus $R=0.63$, $p<0.01$; lateral ROI: right talus $R=0.54$, $p=0.020$; left talus $R=0.75$, $p<0.01$).

Considering tali having a particular grade, the mean trabecular deviation from the vertical was: $7.1^\circ \pm 1.5$ at grade 0 tali; $7.3^\circ \pm 1.2$ at grade 1; $10.9^\circ \pm 2.8$ at grade 2; and $16.2^\circ \pm 3$ at grade 3 for right ankles. For left ankles the means were $5.6^\circ \pm 1.6$ at grade 0; $8.6^\circ \pm 1.5$ at grade 1; $13.4^\circ \pm 2.5$ at grade 2; and 11.50° (1 specimen) at grade 3. Thus, in general, the higher the cartilage degeneration grade, the greater the deviation of the trabecular angle from the perpendicular.

There was a correlation between the age of the subject and the grade of cartilage degeneration ($p=0.01$), but not between the age of the subject and the trabecular deviation ($p=0.13$). Furthermore, there was no correlation between the weight of the subject and the cartilage degeneration grade ($p=0.18$), nor with the weight of the subject and trabecular alignment ($p=0.11$).

The articular cartilage on the talar dome in 8 specimens showed signs of calcification. While the exact association between chondrocalcinosis and cartilage degeneration is unknown^{13,14}, we also analyzed the data with the exclusion of these samples to eliminate any possible confounding effect from the calcinosis. With this data set, the correlation of cartilage degeneration with trabecular deviation of the medial ROI was still found to be quite strong ($R=0.73$, $p<0.001$ for right tali and $R=0.62$, $p=0.02$ for left tali). The grade of cartilage damage compared to the trabecular deviation of the lateral ROI without these calcified samples correlated similarly ($R=0.66$, $p<0.01$ for right tali and $R=0.73$, $p<0.01$ for left tali) to the data that included the calcified talar samples. Furthermore, the total trabecular deviation (sum of medial

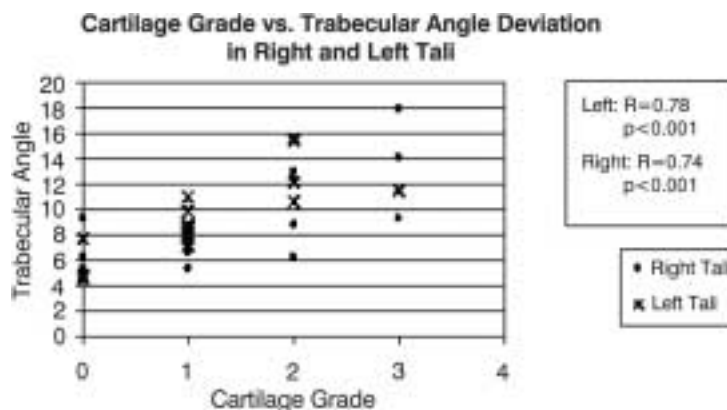


Figure 3. Correlation between cartilage grade and trabecular angle. Scatterplot of the cartilage grade versus the trabecular angle for the right and left tali (mean of the medial and lateral regions of interest). It can be seen that the trabecular angle significantly increases as cartilage degenerate score increases.

and lateral ROIs) correlated to the cartilage degradation score ($R=0.72$, $p<0.01$ for right tali and $R=0.78$, $p<0.01$ for left tali).

There was no correlation between cartilage degeneration and trabecular anisotropy as measured by fast Fourier analysis ($p=0.26$).

Discussion

We chose to investigate the relationship between the trabecular angle within the body of the talus and the level of cartilage degeneration on its trochlear articular surface because of the relationship that each of these two components has individually with biomechanics. Trabecular alignment/angulation is hypothesized to correlate with the direction in which load is transmitted through bone. As such, it follows that the direction of load at a joint may render the joint either more or less susceptible to cartilage degeneration, depending upon whether or not this load is in alignment with the anatomy of the joint¹⁵⁻¹⁷. Thus, it is logical to investigate a possible relationship between trabecular alignment and cartilage degeneration.

Due to the anatomical structure of the talus as the distal component of the ankle joint, it has several different trabecular regions. The talus has no muscle attachments, but articulates with the tibia superiorly and medially, the fibula laterally, the calcaneus inferiorly, and anteriorly with the navicular. The tibia transmits force from standing, walking, and running through the trochlea of the talus, onto its body and then to the calcaneus². Thus, because of the generally vertical forces being transmitted onto the trochlea and, in turn, body of the talus, its trabeculae run predominately vertically, from superior to inferior². Because the talus then also transmits the force anteriorly, to the navicular, there is an abrupt change in the direction of the trabeculae, from a vertical arrangement in its body, to an oblique orientation in the neck. The head of the talus, which articulates with the navicular, has predominately horizontal trabeculae that are continuous with

those of the neck, and run posteriorly to anteriorly².

In the present study we have shown a strong positive correlation between the grade of cartilage degeneration and the trabecular angle associated with the talar trochlea. We assume that the normal angle of the talar trochlea is not perfectly perpendicular to its superior/inferior axis. Indeed, it is likely that very slight deviations are the norm. However, as small as the deviations from the vertical were in our study sample (ranging from approximately 4° to 18°), they were strongly correlated with the level of cartilage degeneration on the articular surface of the trochlea. This correlation was maintained in both the medial and lateral regions of interest within the tali and in tali from both left and right ankles. It was of interest that trabeculae of the tali of the majority of donors ran laterally (in 23 of 38 tali, or in 14 of 18 donors) in both ROIs; and only 2 tali of 2 donors had medially directed tali in both ROIs of an individual talus.

Cancellous bone changes occurring with osteoarthritis (OA) have previously been investigated. It has been reported that significant trabecular remodeling with bone thickening occurs within the femoral head, even with mild cartilage degeneration¹⁸. Furthermore, it has been demonstrated that although bone volume and trabecular thickness increase with OA, trabecular number and trabecular separation decrease¹⁹. To our knowledge, the angle of the trabeculae has not been investigated as it relates to the integrity of the overlying articular cartilage or osteoarthritis.

Most OA of the ankle joint is actually secondary, as a result of injury or trauma. Furthermore, there is only a slight increase in cartilage degeneration of the ankle with age, but not nearly that found in the knee, suggesting that ankle OA is not directly related to age²⁰. OA in the ankle is significantly more prevalent in males than females²¹. The major risk factor for ankle OA is either abnormal mechanics that increase the wear at the articulating surface⁸, or trauma²². In the present study, 92% of the 38 tali, or 72% of the 18 donors displayed cartilage degeneration at the level of fibrillation or greater.

The ankle is an inherently stable joint whose passive motion is guided by the calcaneofibular and tibiocalcaneal ligaments together with the articular surfaces²³. Certainly the full extent of movement at the ankle joint is also determined by the geometrical shapes of surrounding soft tissues as well as the mechanical properties of the bones and soft tissues. The ankle joint is multiaxial, having at least minimal levels of eversion and inversion along with a sagittal plane motion^{24,25} of approximately 24° in the normal joint during the stance phase of gait²⁶. Although the mechanical axis of the ankle is surely variable between individuals, basically, in dorsiflexion, it tends to be oblique downward and lateral.

Because the surrounding soft tissues were not available for most of the specimens, it could not be determined if there were any associated pathologies such as lax ligaments. However, there was no documentation of rupture, or signs of previous surgery. Even so, soft tissue pathologies leading to joint malalignment or laxity would be expected to result in altered biomechanics and, thus, susceptibility to cartilage degeneration. Although there is no previous documentation that the biomechanical status at a joint is associated with trabecular angle, it is our hypothesis that there is a biomechanical connection between trabecular alignment and cartilage degeneration. This biomechanical connection may be in the form of a deviation from what is considered the normal loading pattern or congruence at the ankle joint. Although this alteration may be only a few degrees of deviation, it may have a substantial effect on the congruency of the opposing articular cartilage surfaces. The location of many of the cartilage lesions on the medial and lateral borders of the trochlear articular surface lends credence to this hypothesis. Because the present study is cross-sectional and a biomechanical thread connecting trabecular angle to cartilage degeneration is purely speculative, a discussion is warranted on the association between biomechanical factors and cartilage health.

Risk factors that have been associated with pathogenesis of osteoarthritis include genetic factors, aging, joint deformity, injury, obesity, and other factors such as alterations in the neuromuscular system including abnormal gait, muscle strength, and dynamic joint loading patterns²⁷. Progression of osteoarthritis has been associated with limb malalignment such as varus-valgus alignment²⁸⁻³⁰. One of the most compelling studies on the association between biomechanical factors and knee OA was carried out by Cicuttini et al.³¹ in which it was observed that the angle at the tibiofemoral joint was associated with the rate of cartilage loss in the knee after a follow-up of approximately two years.

The unifying thread of logic among the ideas of the present study is that biomechanics and congruence at joints is related to both trabecular orientation and cartilage integrity. As trabecular orientation is a reflection of the history of stresses on a specified bone, so too are the integrity of the bone and, thus, overlying cartilage, a reflection of these stresses. To reiterate, cause and effect are not shown here. However, a significant association between trabecular angle, as a history of direction of bone load, and cartilage integrity

is shown. Whether this is related to congruence of the articular surfaces at the apposing surfaces or to altered forces can not be shown in this cross-sectional study.

Because the FFT program used here examines the distribution of the angles within a region of interest based on a power spectrum generated using segments that correspond to increments of one degree of orientation, the program is sensitive to any rotation of the specimen being measured. Great care was taken when establishing the superior axis of each talus, to which the perpendicular axis and, in turn, trabecular angles were compared. Thus, if the superior axis of the talus was measured inaccurately, the FFT measurements would be inaccurate. However, any inaccuracies in the establishment of the superior axis would most likely be systematic, and thus, consistent throughout, thus effecting all results equally. But we will not dismiss this issue entirely; rather we maintain that it should be kept in mind when interpreting the present results.

A limitation of the study is that only 38 tali from 20 donors were utilized. However, even with this number of specimens, our correlations were quite high, with significance of $p < 0.01$. Another limitation of the study was that we only had 3 tali displaying grade 3 cartilage degeneration and none at grade 4. This was due to the fact that very few tali display severe cartilage degeneration, as primary OA of the ankle joint is rare. Because this study is cross-sectional and, thus, does not allow discrimination of cause and effect, the only claim to be made is that an association was found between the level of articular cartilage degeneration on the talar trochlea and the angle of the trabeculae beneath this cartilage.

The clinical significance of our current finding is debatable. Despite the overall correlation, there were still some tali deviating from a direct relationship between trabecular angle and level of cartilage degeneration. Thus, one cannot necessarily assume that a patient with a higher trabecular angle also has cartilage degeneration. We would not suggest X-ray with subsequent trabecular angle measurement as a screening tool or as a predictive tool, particularly since ankle cartilage degeneration may be asymptomatic. However, our results do support an association between trabecular alignment and the level of cartilage degeneration.

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