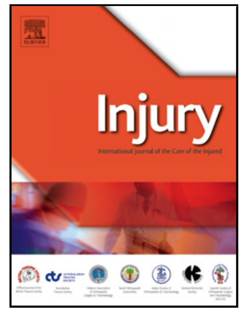
Accepted Manuscript



Title: Does the relative density of periarticular bone influence the failure pattern of intra-articular fractures?

Author: K.D. Tetsworth A.Y. Borshch C.E. Dlaska E. Hohmann

PII: S0020-1383(16)30182-6
DOI: http://dx.doi.org/doi:10.1016/j.injury.2016.05.014
Reference: JINJ 6727

To appear in: *Injury, Int. J. Care Injured*

Accepted date: 9-5-2016

Please cite this article as: Tetsworth KD, Borshch AY, Dlaska CE, Hohmann E.Does the relative density of periarticular bone influence the failure pattern of intra-articular fractures?.*Injury* http://dx.doi.org/10.1016/j.injury.2016.05.014

Does the relative density of periarticular bone influence the failure pattern of intra-articular fractures?

Tetsworth KD[1, 3] , Borshch AY[1, 3], Dlaska CE [4], Hohmann E [2, 3]

(1) Department of Orthopaedic Surgery, The Royal Brisbane and Women's Hospital, Brisbane, Australia

(2) Musculoskeletal Research Unit, Central Queensland University, Rockhampton, Australia

(3) University of Queensland, School of Medicine, Brisbane, Australia

(4) Department of Trauma, General Hospital of Vienna, Medical University of Vienna, Austria

Corresponding author:

Erik Hohmann

PO Bo 4045

Rockhampton QLD 4700

Email: ehohmann@optusnet.com.au

Running title: Periarticular Bone Density and Intra-articular Fractures

Abstract:

Introduction: The architecture of joints almost certainly influences the nature of intra-articular fractures, and the concavity is much more likely to fail than the associated convexity. However, local differences in periarticular bone density potentially also plays a critical role. The purpose of this study was to investigate if there was any difference in periarticular bone density in intra-articular fractures between the two opposing joint surfaces, comparing the convexity to the concavity.

Materials and Methods: We retrospectively identified a series of 1,003 intra-articular fractures of the hip, knee, and ankle; 129 of these patients had previously undergone CT scanning during their routine clinical assessment. Periarticular bone density was assessed using Hounsfield Units (HU) as a measure of the composite density of the adjacent bone. Bone density was compared between the opposite sides of each joint, to determine if a relationship exists between local bone density and the risk of articular surface fracture.

Results: There was a statistically significant difference in density between the two opposing surfaces, with the convexity 19% more dense than the concavity (p=0.0001). The knee exhibited the largest difference (55%), followed by the hip (18%); in the ankle, an inverse relationship was observed, and the concave surface was paradoxically denser (5%). There was no significant difference between those cases where the concavity failed in isolation compared to those where the convexity also failed ($p = 0.28$).

Conclusion: When the results were pooled for all three joints, there was a statistically significant higher local bone density demonstrated on the convex side of an intra-articular fracture. However, while this relationship was clearly exhibited in the knee, this was less evident in the other two joints; in the ankle the reverse was true, and the local bone adjacent to the concavity was found to have greater density. This suggests local bone density plays only a minor role in determining the nature of intra-articular fractures.

Key words: Intra-articular fractures; trauma; biomechanics; bone density

Introduction:

When the major joints of the lower limb are subjected to an abnormal axial load to the point of failure it is most often the concave side of the joint that fractures [25]. In clinical practice fractures of the tibial pilon, tibial plateau, and acetabulum far more commonly observed than fractures of the matching talus, femoral condyles and femoral head [25]. During any traumatic injury event Newtonian mechanics dictate that both surfaces are subjected to an equal and opposite force; why, then, does one side fail so much more often?

Loads applied to the surface of a convexity are converted to compressive forces by the geometry of the macrostructure [23], and bone tolerates compressive loads very well [2,3,4,8,19,24]. If instead loads are applied from within a concavity the macrostructure is subjected to tensile forces [23]. When loaded in tension bone provides far less structural support, and fails under much smaller loads [2,3,4,8,19,24].

Another potential mechanism for the preferential failure of the concavity may be a discrepancy in local bone density. Frost has proposed that bone growth, remodelling, and trabecular patterns very closely follow the loads applied to that bone [6,7]. Areas of higher stress during normal physiological loads become denser than those areas subjected to lesser stress, as can be seen in impact-loading athletes; their distal tibiae exhibit significantly higher bone density, cortical thickness, and load to failure, as compared to controls from non-load-bearing athletes [21].

For example, Haverstock, et al. [9], demonstrated the anterolateral quadrant of the radial head has the lowest bone density and is also correspondingly the region most prone to fracture. The posteromedial quadrant is an area of greater load bearing, with the highest bone density; this was the least likely region to fracture [9]. Iwasaki, et al. observed a statistically significant between group difference in bone mineral density in patients with insufficiency fractures that showed either progression or no progression of the disease, with those who progressed having a lower bone mineral density [11].

Local differences in bone density may be an important consideration, although the architecture of the surrounding bone has already been identified as a significant factor in determining the pattern of failure observed in intra-articular fractures [25]. The purpose of this study was therefore to investigate whether the relative density of local bone on the two opposite sides of a joint is associated with failure of the less dense side. We hypothesized that there would be no significant differences in bone density when comparing the concavity to the convexity as matched pairs on the opposing surfaces of an intra-articular fracture.

Materials and Methods:

IRP Approval was obtained from our institutions Human Research Ethics Committee. In a previous publication we have identified 1,003 intra-articular fractures, and reported that 95% of all intra-articular fractures involved the concave surface of the joint [25]. The inclusion criteria here included fractures of the hip, knee or ankle. Upper extremity fractures were specifically excluded. From a subset of 368 lower extremity fractures which all had undergone CT scanning as a routine part of their clinical care, a random sample of 129 cases was selected. An a-priori sample size calculation indicated that a random sample selection of 94 cases was needed to limit the margin of error to five percent. A further sample size analysis indicated that 72 cases were needed to detect a 20% difference in bone density between the concave and convex joint surface (two sided alpha=0.05, power 0.9). The current study is restricted exclusively to this subset of cases, and periarticular bone density was specifically examined on both sides of each of these 129 cases.

Periarticular bone density adjacent to both the concave and convex sides of each joint was measured in Hounsfield units. This measure has been shown to be an accurate and reproducible estimate of bone mineral density, and compares favourably to either dual x-ray absorptiometry or to mechanical testing of subchondral bone strength [15,16,17,22,26]. Measurements were done using the standard tools of the IMPAX (AGFA HealthCare, Greenville, SC, USA) radiology imaging software package. The oval HU tool allows a particular region of bone to be selected, displaying the length and width of the region under observation (Fig 1). The software simultaneously calculates the area covered while also providing a measure of the mean Hounsfield units of the region circumscribed by the tool at any time. In addition to the bone density measured in each case, we further recorded routine demographic information including the patients' age, gender, the joint affected, the side of the body injured, and the surface of the joint involved (concavity or convexity).

Observations were conducted using a rigorously standardized technique to minimize the risk of introducing any measurement bias. No observations were conducted within 3 mm of the fracture site itself, to avoid the potential effects of local bone compaction, comminution, or fracture gaps. The margins of each joint were avoided, and no measurements were made within 5 mm of the periphery of a joint. The oval HU tool was maintained as a constant size and shape for any given case; all ten observations, five on each side of every joint, were conducted by translating the same size and shape oval tool to a separate and distinct area of bone for each measurement. The oval shape was selected specifically to limit potential duplication of regions of bone covered, difficult to avoid with a circular shape. The selected oval configuration was 7 to 12 mm in length, and 2.5 to 3.5 mm in width, with a target width to length ratio of 0.3. The tool was carefully positioned immediately beneath the articular surface to capture both the subchondral plate as well as periarticular cancellous bone, recognizing both contribute to local bone density. The tool was positioned perpendicular to the joint surface, to facilitate consistency of observations incorporating both the subchondral plate and periarticular cancellous bone.

Two independent research associates performed all measures. Five independent measurements were recorded on both sides of every joint by each of the investigators, and the highest and lowest values on each side were dismissed; data analysis was conducted on the three remaining values, and a mean calculated. To establish inter- and intra-observer reliability, two investigators used the methods described in 20 randomly selected cases and correlation coefficients were calculated. The correlation coefficients for intra-observer reliability were 0.95 for the concave and 0.96 for the convex surface measurements for examiner one, and 0.86 (concave) and 0.91 (convex) for examiner two. The inter-observer correlation coefficient was 0.63. Given the rather poor inter-rater coefficient correlations and the moderate ICC for examiner two, only measures from examiner one were used for analysis.

Means, standard deviations, and 95% confidence intervals were calculated for the demographic variables and dependent variables derived from the bone density measures. For further analysis the bone density measures were subdivided into the three different anatomical regions (hip, knee, ankle), and if required differentiated into fracture location (concavity, convexity). Normality of the bone density variables was established by performing a Shapiro-Wilks test. A series of paired two-sample t-tests were then used to compare each of the continuous variables within each patient. In the event of a significant ($p < 0.05$) main effect for the subdivided anatomical regions and fracture location, *post hoc* comparisons of the means were conducted using the least significant difference (LSD) test to delineate differences amongst anatomical regions and fracture locations. Alpha level correction using Bonferroni were conducted to correct for familywise error. All statistical analyses were performed using STATA SE (Version 12.0; StataCorp, College Station, Texas, USA) for Windows.

Results:

The mean age of the cohort was 42.6±17.7 years. There were 105 males and 24 females. There were 50 hip fractures (n=45 concave surface/acetabulum; n=5 convex surface/femur) with a mean age of 45.6±20.5 years (40 males, 10 females), 42 knee fractures (n=33 concave surface/tibial plateau; n=9 convex surface/femoral condyles) with a mean age of 41.5+18.3 years (28 males, 13 females) and 37 ankle fractures (n=33 concave surface/tibial plafond; n=4 convex surface/talus) with a mean age of 39.8+11.9 years (36 males, 1 female). The majority of these fractures, 111 cases (86%), affected only the concave surface. 45 hip fractures (acetabulum), 42 knee fractures (tibial plateau) and 33 ankle fractures (tibial plafond) occurred on the concave surface. In five cases the convex surface of the hip (femur), in seven cases the convex surface of the knee (femoral condyles) and in six cases the convex surface of the ankle (talus) had fractured.

Statistical analysis revealed significant differences in bone density between the concave and convex joint surface (convexity 19% more dense) (Fig.2) for the following locations: all fractures (n=129) p=0.0001; hip fractures (n=50) p=0.0001; all knee fractures (n=42) p=0.0001, knee concavity fractures (n=33) p=0.0001; knee convexity fractures (n=9) p=0.003; ankle all fractures (n=37) p=0.006; ankle concavity fractures (n=33) p=0.002, ankle convexity fractures (n=4) p=0.87. For the hip bone density of the fractured joint surface was significantly (p=0.0001) less dense (18%). For the knee the convex joint surface was significantly (p=0.0001) more dense (55%). Despite these significant differences in bone density, fractures of the convex surface were observed in 22 percent. In the ankle there was no significant difference between the overall joint surface bone density. However with further analysis the concave surface was significantly (p=0.002) more dense (69%) in convexity fractures indicating that the denser surface similar to the hip influences fracture location. For fractures involving the concave surface of the ankle the bone density differences between the convex and concave surface were minor and non-significant. The concave surface was 5% more dense.

Discussion:

The most important finding of this study was that the relationship between bone density and joint architecture was not consistently demonstrated in these three different anatomic locations. Although overall the local bone density associated with a convexity was greater than that associated with its corresponding paired concavity, significant differences were noted that are site specific. In the knee, the bone immediately adjacent to the convex articular surface of the distal femoral condyle was clearly denser than the bone adjacent to the associated concave tibial plateau. However, in the hip the bone within the convex femoral head was only moderately denser than the bone forming the corresponding concave acetabulum. Somewhat unexpectedly, the bone forming the concavity of the distal tibial plafond was in fact denser than the bone within the convexity of the associated talar dome.

Intra-articular fractures of the lower limb can often be difficult to manage successfully, both in terms of initial surgical fixation and with respect to potential long-term post-traumatic morbidity. Treatment of these fractures, both operative and non-operative, can have high complication rates, reportedly between 27% and 54% [5,13,14,2,27]; high rates of revision surgery, reportedly from 10% to 23% [5,10,12]; and significant residual dysfunction [1,12,18]. Some of these problems are almost certainly related to damage to the overlying articular cartilage, which inevitably sustains additional injuries during the initial event. A better understanding of the mechanism by which these fractures occur may be pivotal in improving both prevention and treatment of these debilitating injuries. We know that fractures of the ankle, knee and hip tend to occur in certain patterns, and fractures of the concave side of these joints (acetabulum, tibial plateau and tibial pilon) occur much more frequently than fractures of the convex side (femoral head, femoral condyles and talus) [25]. However, it is not clear whether the mechanism of injury, three-dimensional joint architecture, local bone density, or other factors are the main contributors to the observed preferential failure of the concavity.

In this study we found overall the periarticular bone density was significantly lower on the concave side of these joints, suggesting the normal physiologic loads applied through the concavity are less than those applied through the convexity [6,7]. As noted, this was most pronounced in the knee and was less obvious in the hip and ankle. This may reflect the different nature of the principal loads applied to a convexity compared to a concavity, as a result of structural properties integral to the three dimensional configuration of these opposing surfaces. In the hip (Fig. 3), the concavity of the acetabulum results in divergent forces in the adjacent bone creating tension stresses that most often result in an acetabular fracture. Similar, in the knee (Fig. 4) the mild concavity of the tibial plateaus result in divergent forces in the adjacent bone with axial loads resulting in tibial plateau fractures. In the ankle (Fig. 5), the axial loads result in tension forces on the concavity of the tibial plafond creating tension forces resulting in tibial plafond fractures. In contrast, the convexity of the femoral head in the hip, the femoral condyles in the knee and the superior aspect of the talus result in convergent forces in the adjacent bone. These forces create compressive stresses that are less likely to result in fractures. This is a concept that has not yet been fully explored, and further research in this area will be necessary to determine its potential significance.

The principal limitation of this study is the relatively small size of the study cohort. Although derived from an initial pool of over 1,000 intra-articular fractures, only 13% of these had previously undergone a CT scan as part of their routine clinical evaluation. However, the additional cost and significant radiation risk associated with diagnostic CT scans makes this entirely impractical to consider as a research investigation. While it is possible selection bias may have influenced the outcome, we have included all patients who satisfied the inclusion criteria and believe this is unlikely.

Conclusion:

When the results were pooled for all three joints, there was a statistically significant higher local bone density demonstrated on the convex side of an intra-articular fracture. However, while this relationship was clearly exhibited in the knee, this was less evident in the other two joints; in the ankle the reverse was true, and the local bone adjacent to the concavity was found to have greater density. This suggests local bone density plays only a minor role in determining the nature of intra-articular fractures.

Disclosures: The authors have no conflicts of interest to report related to the current study.

Level of Evidence: III

Acknowledgment:

We would like to thank Dr Vaida Glatt, PhD (Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Queensland, Australia) for her assistance with the creation of the figures.

References:

1. Barei D, Nork S, Mills W: Functional outcomes of severe bicondylar tibial plateau fractures treated with dual incisions and medial and lateral plates. J Bone Joint Surg (Am) 2006; 88A:1713-1721.

2. Carter DR, Hayes WC: The compressive behavior of bone as a two-phase porous structure. J Bone Joint Surg (Am) 1977; 59A:954-962.

3. Carter DR, Caler WE, Spengler DM, Frankel VH: Fatigue behavior of adult cortical bone: the influence of mean strain and strain range. Acta Ortho Scand 1981; 52:481-490.

4. Currey JD, Brear K: Tensile yield in bone. Calc Tiss Res 1974; 15:173-179.

5. Daurka JS, Pastides PS, Lewis A, et al. Acetabular fractures in patients aged > 55 years: a systematic review of the literature. Bone Joint J 2014; 96B:157-63.

6. Frost HM: Bone "mass" and the "mechanostat": a proposal. Anat Rec 1987; 219:1-9.

7. Frost HM: Bone's mechanostat: a 2003 update. Anat Rec A Discov Mol Cell Evol Biol 2003; 275:1081-101.

8. Gupta HS, Zioupos P: Fracture of bone tissue: the 'hows' and the 'whys'. Med Engin Physics 2008; 30:1209-1226.

9. Haverstock JP, Katchky RN, Lalone EA, Faber KJ, King GJ, Athwal GS: Regional variations in radial head bone volume and density: implications for fracture patterns and fixation. J Shoulder Elbow Surg 2012; 21:1669-73.

10. Hayes PJ, Carroll CM, Roberts CS, et al. Operative treatment of acetabular fractures in the Medicare population. Orthopedics 2013; 36:e1065-70.

11. Iwasaki K, Yamamoto T, Motomura G, Ikemura S, Yamaguchi R, Iwamoto Y: Radiologic measurements associated with the prognosis and need for surgery in patients with subchondral insufficiency fractures of the femoral head. Am J Roentgenol 2013; 201:W97-W103.

12. Marsh J, Weigel D, Dirschl D: Tibial Plafond Fractures How Do These Ankles Function Over Time? J Bone Joint Surg (Am) 2003; 85A:287- 295.

13. McFerran M, Smith S: Complications encountered in the treatment of pilon fractures. J Orthop Trauma 1992; 6:195-200.

14. Moore T, Patzakis M, Harvey J: Tibial plateau fractures: definition, demographics, treatment rationale, and long-term results of closed traction management or operative reduction. J Orthop Trauma 1987; 1:97-119.

15. Mueller F, Hoechel S, Klaws J, Wirz D, Müller-Gerbl M: The subtalar and talonavicular joints: a way to access the long-term load intake using conventional CT-data. Surg Radiol Anat 2014; 36:463-472.

16. Mühlhofer H, Ercan Y, Drews S, Matsuura M, Meissner J, Linsenmaier U, Putz R, Müller-Gerbl M: Mineralisation and mechanical strength of the subchondral bone plate of the inferior tibial facies. Surg Radiol Anat 2009; 31:237-43.

17. Müller-Gerbl M, Putz R, Hodapp N, Schulte E, Wimmer B: Computed tomography-osteoabsorptiometry for assessing the density distribution of subchondral bone as a measure of long-term mechanical adaptation in individual. Skeletal Radiol 1989; 18:507–512.

18. Pollak AN, McCarthy ML, Bess RS, Agel J, Swiontkowski MF: Outcomes After Treatment of High-Energy Tibial Plafond Fractures. J Bone Joint Surg (Am) 2003; 85A: 1893-1900.

19. Reilly DT, Burstein AH: The elastic and ultimate properties of compact bone tissue. J Biomech 1975; 8:393-405.

20. Ruffolo MR, Gettys FK, Montijo HE, Seymour RB, Karunakar MA: Complications of High-Energy Bicondylar Tibial Plateau Fractures Treated with Dual Plating Through Two Incisions. J Orthop Trauma 2015; 29 (2):85-90

21. Schipilow JD, Macdonald HM, Liphardt AM, Kan M, Boyd SK: Bone micro-architecture, estimated bone strength, and the muscle-bone interaction in elite athletes: an HR-pQCT study. Bone 2013; 56:281-9.

22. Schreiber JJ, Anderson PA, Rosas HG, Buchholz AL, Au AG: Hounsfield units for assessing bone mineral density and strength: a tool for osteoporosis management. J Bone Joint Surg (Am) 2011; 93A:1057-63.

23. Seward D: Understanding Structures, 2nd Ed Palgrave, Basingstoke, Hampshire, UK, 1998.

24. Simkin A, Robin G: The mechanical testing of bone in bending. J Biomech 1973; 6:31-39.

25. Steer RA, Smith SD, Lang A, Hohmann E, Tetsworth K: Does Joint Architecture Influence the Nature of Intra-articular Fractures? Injury 2015, 46 (7):1299-1303.

26. Tay W-L, Chui C-K, Ong S-H, Ng AC: Osteoporosis screening using areal bone mineral density estimation from diagnostic CT images. Acad Radiol 2012; 19:1273-82.

27. Young MJ, Barrack RL: Complications of internal fixation of tibial plateau fractures. Orthop Rev 1994; 23:149-154.

Figure Legends

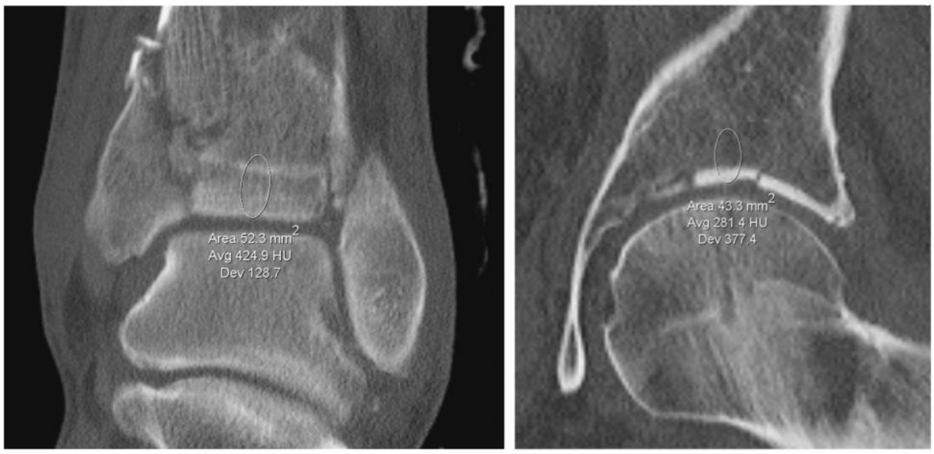


Figure 1: Periarticular bone density measurement using the oval HU tool. The tool was positioned immediately beneath the articular surface to capture both the subchondral plate as well as periarticular cancellous bone, recognizing both contribute to local bone density.

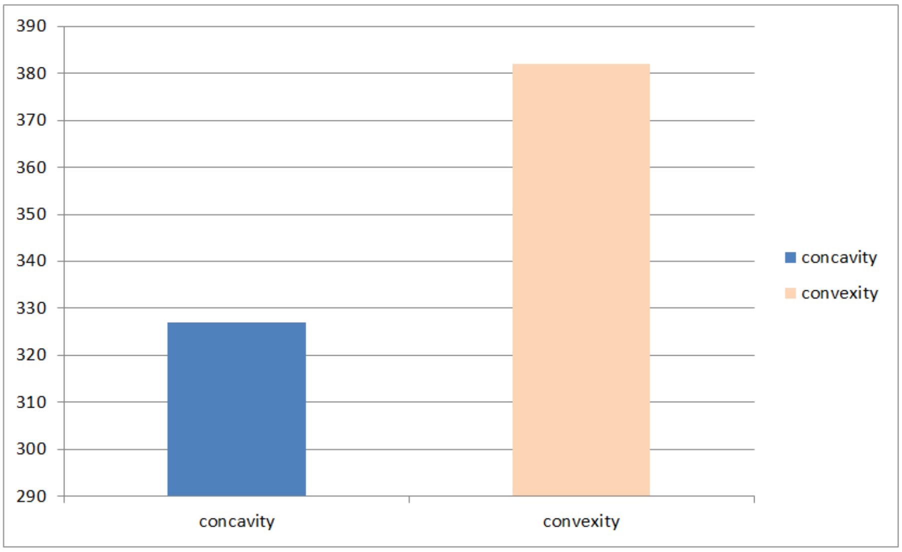


Figure 2: Mean bone density for all fractures (hip, knee and ankle) for both the concave and convex surface. The convex joint surface is 19% denser when compared to the concave surface.

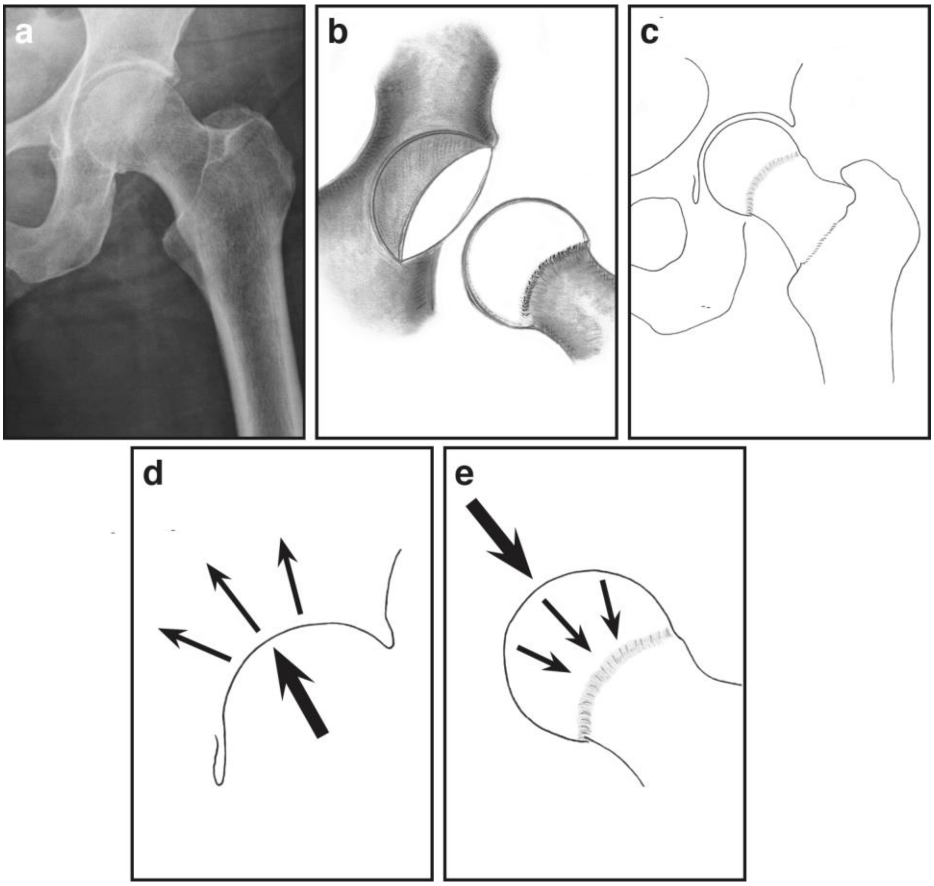


Figure 3: **(a)** Typical AP radiograph of an adult hip. **(b)** Stylised 3D rendering of the hip, emphasising the ball and socket nature of the joint. The femoral head is nearly spherical, and a concavity is paired with a convexity in multiple planes. **(c)** Corresponding line drawing from the AP radiograph of the hip. **(d)** The concavity of the acetabulum; axial loads across this joint surface result in divergent forces in the adjacent bone. These forces create tension stresses that most often result in an acetabular fracture. **(e)** The convexity of the femoral head; axial loads across this joint surface result in convergent forces in the adjacent bone. These forces create compressive stresses that are far less likely to result in a femoral head fracture.

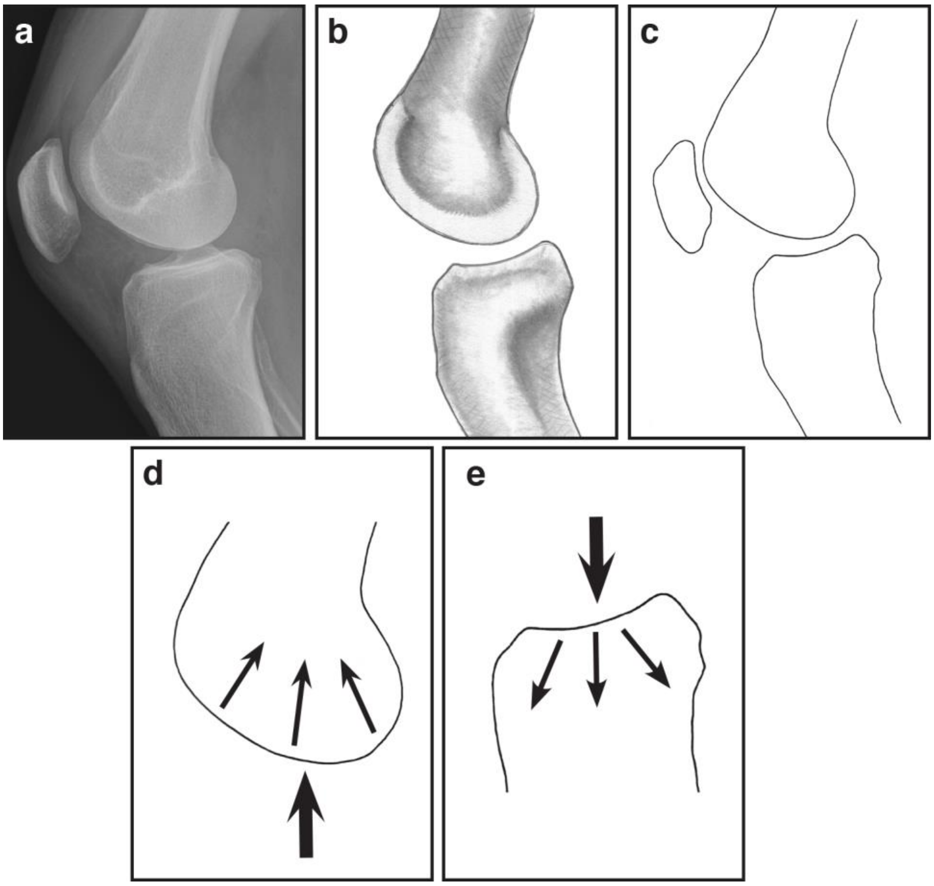


Figure 4: **(a)** Typical lateral radiograph of an adult knee. **(b)** Stylised 3D rendering of the knee, and it is apparent this relationship is least like a ball and socket. Although a concavity is paired with a convexity, the proximal tibia provides only a shallow socket. **(c)** Corresponding line drawing from the lateral radiograph of the knee.

(d) The convexity of the femoral condyle; axial loads across this joint surface result in convergent forces in the adjacent bone. These forces create compressive stresses that are less likely to result in a femoral condylar fracture. **(e)** The mild concavity of the tibial plateau; axial loads across this joint surface result in divergent forces in the adjacent bone. These forces create tension stresses that most often result in a tibial plateau fracture.

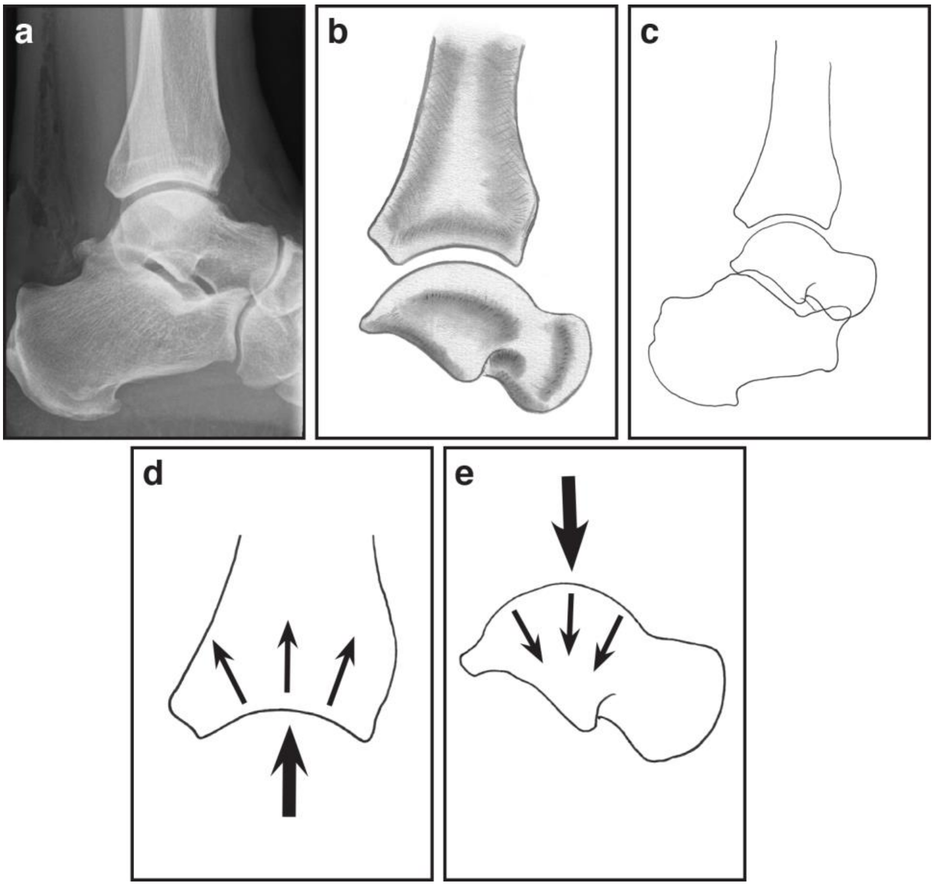


Figure 5: **(a)** Typical lateral radiograph of an adult ankle. **(b)** Stylised 3D rendering of the ankle, and the relationship here is a ball and socket only in the sagittal plane; the concavity is closely paired with a convexity that is most evident in the lateral view. **(c)** Corresponding line drawing from the lateral radiograph of the ankle. **(d)** The concavity of the distal tibial plafond; axial loads across this joint surface result in divergent forces in the adjacent bone. These forces create tension stresses that most often result in a pilon fracture. **(e)** The convexity of the superior aspect of the talus; axial loads across this joint surface result in convergent forces in the adjacent bone. These forces create compressive stresses that are less likely to result in a talar dome or talar body fracture.