THE BEHAVIOR OF THE PATELLA UNDER IMPACT LOADS: THE BIOMECHANICS OF ITS BONY AND CHONDRAL FRACTURE PATTERNS

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Introduction

Fractures of the patella from impact loading, particularly from road accidents, are extremely common. The patella is also extremely commonly subjected to chondral fracture, not often seen in other joints. We propose to relate the pattern of bony fracture of the patella to its trabecular architecture and to relate the peculiarities of the functional anatomy of the patella to the observed high incidence of chondral injury.

Bony Fractures

Ten normal kneecaps obtained at autopsy were freed of soft tissue, fixed in absolute alcohol, impregnated with methylmethacrylate and then sectioned with a diamond wheel, 800 microns in thickness taking slices averaging 220 microns separated by approximately 1 millimeter. The thickness of each slice was then reduced to 80 microns by metallographic polishing and grinding using silicone carbide lubricated with water in successively finer grades. Microradiographs were made of the sections. Horizontal, saggital and frontal sections were all taken to allow a 3 dimensional view of the trabecular organization of the bone.

Nine areas were selected for intensive study as shown in the frontal view in figure 1. Three areas were also located with reference to major articular regions of the patella: the medial facet, the lateral facet and the crest. In order to study the orientation of this structure steriology was used. We used the technique of Underwood where a "rose" of a number of intersections, that is a polar plot of the angle of the test line versus the intersection frequency is generated. The intercept frequency and line fraction was measured for each line. Twenty-four observations were made for each selected area. The horizontal section suggests that the essential elements in the structures were oriented sheets interconnected with the rod like elements (fig. 2). Scanning electron micrographs were taken which confirmed this model.

In some areas it was obvious that we were dealing with a highly oriented trabecular structure. However, other areas showed no apparent organization. If one keeps the structural model in mind it is apparent that one must differentiate between the sheets and the rods. What gives an essentially randomly oriented 3-dimensional structure when one considers the essential element to

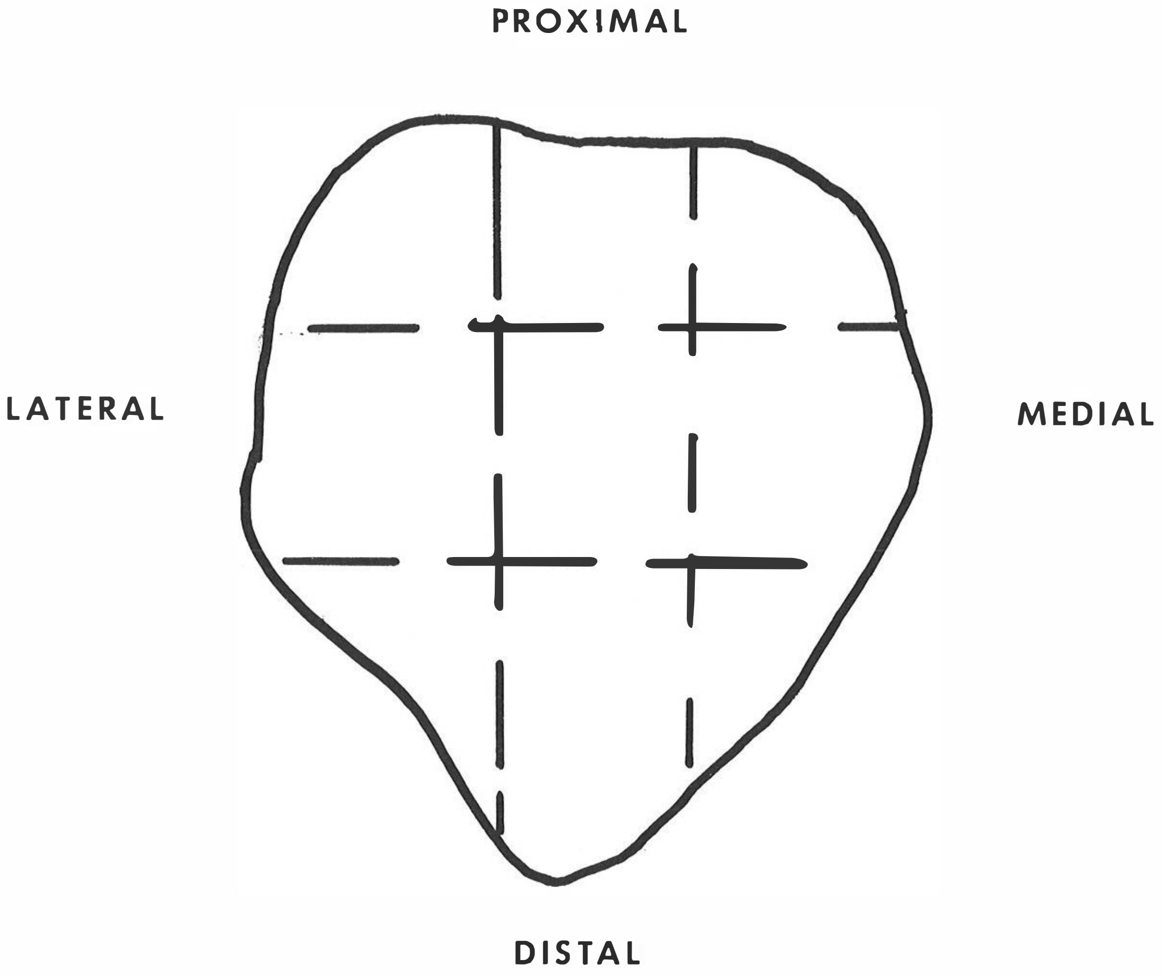


FIG. 1

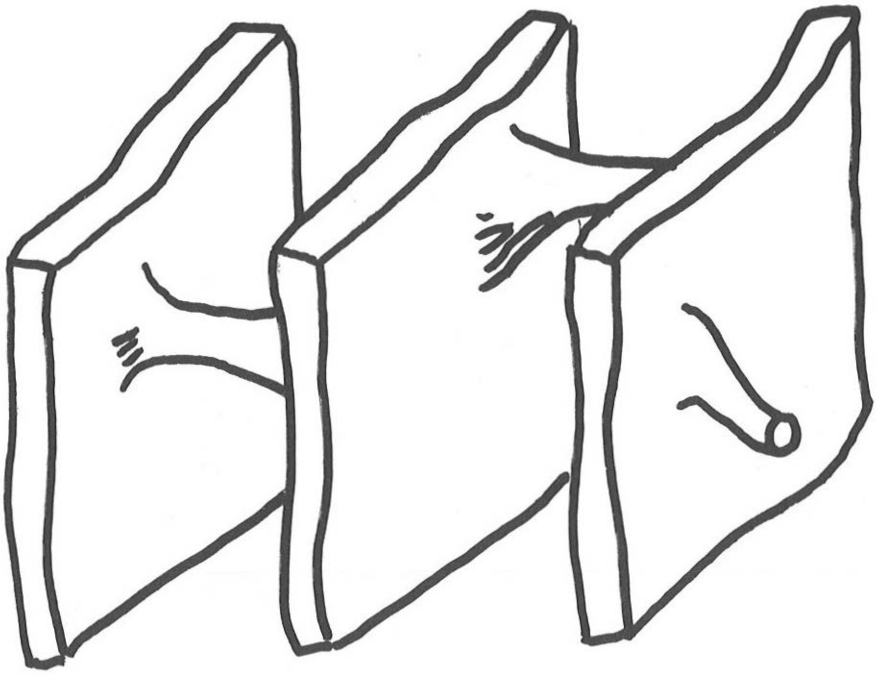


FIG. 2

be the sheets. One must look 3-dimensionally at each area in order to be able to differentiate the orientation of the rods and sheets. This can be accomplished steriologically without difficulty.

The specific results of our measurements indicated that the thickness remained quite consistant. There was also a well defined sub-cortical zone (fig. 3). The geometry suggests that the structure of this sub-cortical zone is determined by the transmission of tensile forces. It was also noted that the controlling parameter in bone density was the distance between the sheets and that the sheet thickness remained relatively constant.

In the frontal view there were 5 regions which could be characterized by a single orientation axis (fig. 4). The upper and lower regions of the medial side consisted for the most part of horizontal sheets running from the articular surface to the anterior cortex which remained approximately orthogonal to the articular surface and were not influenced by the high curvature of the medial side.

The upper and middle portions of the lateral side and the mid-crest region had vertical sheets which ran perpendicular to the articular surface. These sheets extended from the articular side to the cortex. It would seem that these areas would be optimal for transmitting compressive force. The top of the crest was made up of two kinds of sheets. The more lateral ones oriented vertically; the more medial ones becoming more oblique and connected with the

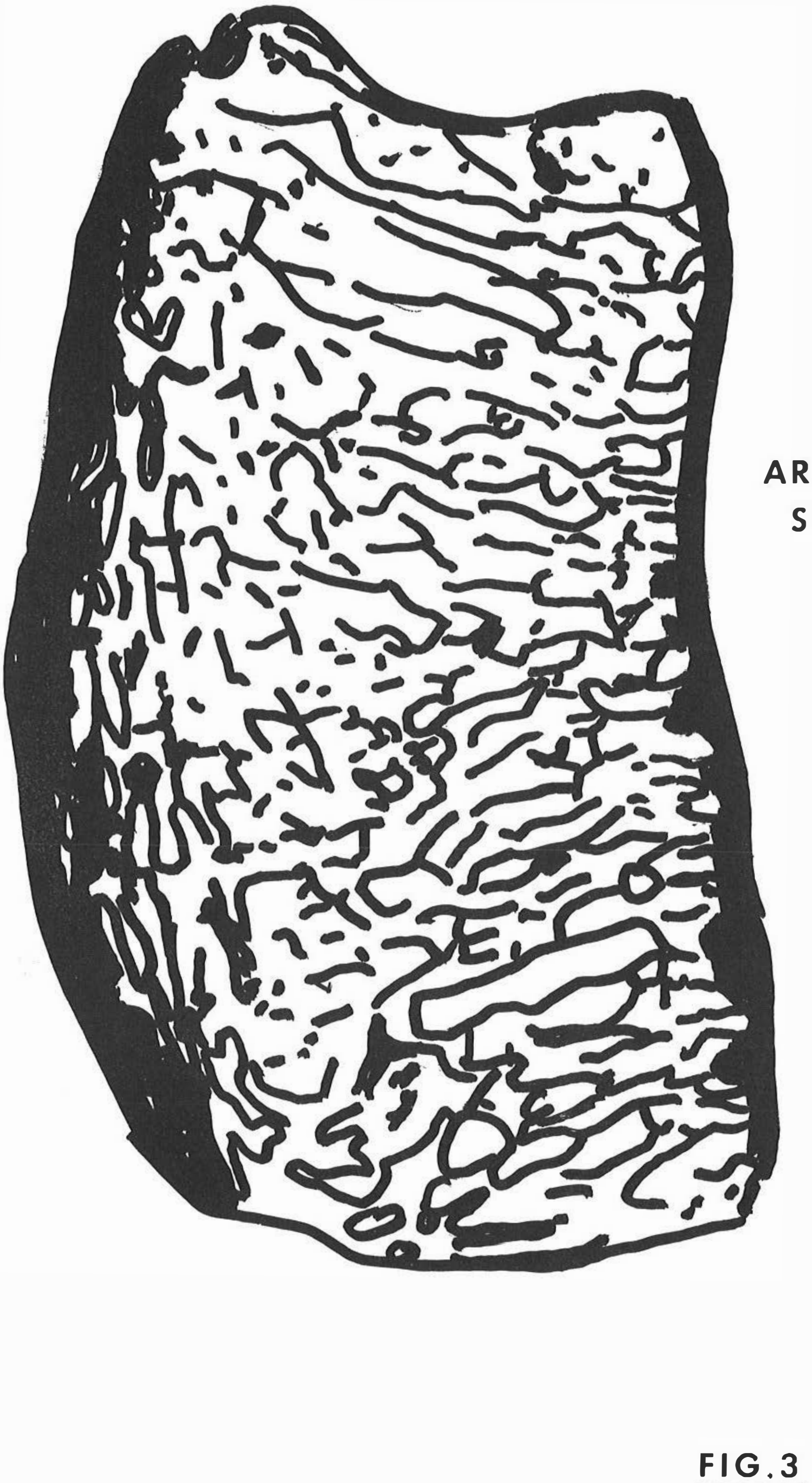


FIG.3

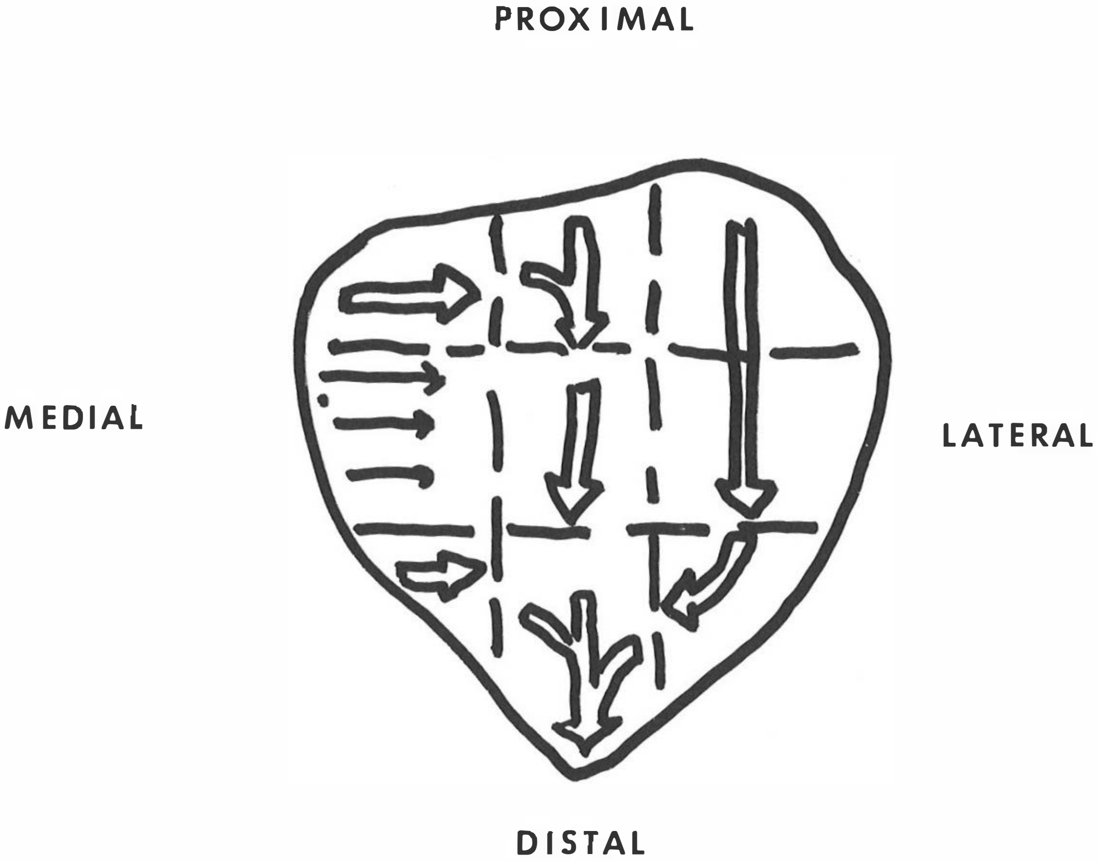


FIG. 4

Milgram. He suggests that the mechanism of osteochondral fracture is a momentary subluxation of the patella laterally. When as it rides back to its natural position Milgram claims that the lateral femoral condylar ridge acts as an anvil on which a fragment of the crest of the patellar is broken off. We have no reason to disagree with his analysis. What we wish to discuss are different injuries.

Trabecular bone and articular cartilage are viscoelastic in their response of applied stress (Radin, Paul, Lowy). Thus at high strain rates both will act in a relatively brittle fashion. As the patella is loaded compressively, the tensile forces will be greatest at right angles, in other words in the frontal plane. If one drops a weight on a bone-cartilage composite and measures the peak dynamic force attenuation at the base of this composite, one can find that the presence or absence of articular cartilage contributes nothing significant to the attenuation of this peak dynamic force or in fact the overall deformation of the system (Radin and Paul 1970). Cartilage compression depends upon a finite amount of time necessary for water to flow out of the cartilage. Cartilage is not very permeable to water flow, thus at high strain rates the cartilage will be subjected to significant tension particularly in the mediolateral plane.

In order to understand the resistance of articular cartilage to tension one must understand the organization of its fibrous structure. This structure is composed of collagen. The nature of the collagen organization in articular cartilage under compression has recently been illucidated by McCall using a scanning electron microscope. It is found to be somewhat at variance with the Benninghoff model (fig. 6). The collagen at the surface is tangential to the surface. The middle zone collagen is randomly oriented, however, under load this orientation of the middle zone becomes generally normal to the load. The basilar collagen is mainly perpendicular to the surface of the cartilage and would seem to anchor the articular cartilage to its calcified bed. Therefore the fibrous structure of articular cartilage is not ideally oriented to resist tension parallel to the surface. Once small microcracks occur in the surface there are relatively few fibers oriented normal to the tensile stress to resist crack propagation. In normal use articular cartilage is remarkably resistant to wear, due to its superb lubricating mechanisms which to a large extent prevent the articular cartilage from becoming stressed in shear. In our laboratory we have run joints in machines under maximal loads for several weeks without producing any demonstrable wear in articular cartilage or change in the coefficient of friction (Radin and Paul, 1971). Even when substituting buffered saline for synovial fluid as the lubricant, hydrostatic mechanisms within articular cartilage maintain its lubricating film even in the presence of high loads and protect the articular surfaces from contact (Radin, Paul and Pollock). They are thus spared high shear forces. We have measured the coefficients of friction in articulating joints and found them to approximate .0005.

If the strain rate is high enough, the cartilage cannot deform out of the way under these circumstances, and it is quite conceivable that the squeeze film trapped between the articular cartilage surfaces could well transmit compression. In view of the fact that the articular cartilage's collagenous organization is poorly organized to resist the resulting tension which will occur normal to this compression,it is quite easy to see how chondral fractures could occur.

horizontal structures of the adjoining area. Throughout this region the sheets retained the same anterior-posterior direction orthogonal to the articular surface. The distal part of the lateral side and the medial side where made up of oblique systems of sheets connecting the vertical sheets of the mid-lateral aspect and the horizontal sheets of the mid-medial aspect to the more or less vertical sheets of the crest area. Thus in the distal polar area there is considerable change of the trabecular orientation.

In figure 5 the analysis of 196 fractures of the patella by Scott is presented. It will be noted that the most common fracture is that of the lower part of the patella, the second most common is a comminuted fracture. Transverse fractures occurring usually in an area about 3/5 of the way down the patella were the third most common. Vertical fracture, polar fracture and fracture of the upper part made up the remainder of the cases.

ANALYSIS OF 196 FRACTURES OF THE PATELLA

Comminuted Fracture	Fracture Upper Part	Fracture Lower part	Transverse Fracture	Vertical Fracture	Polar Fracture
50	14	54	23	13	18

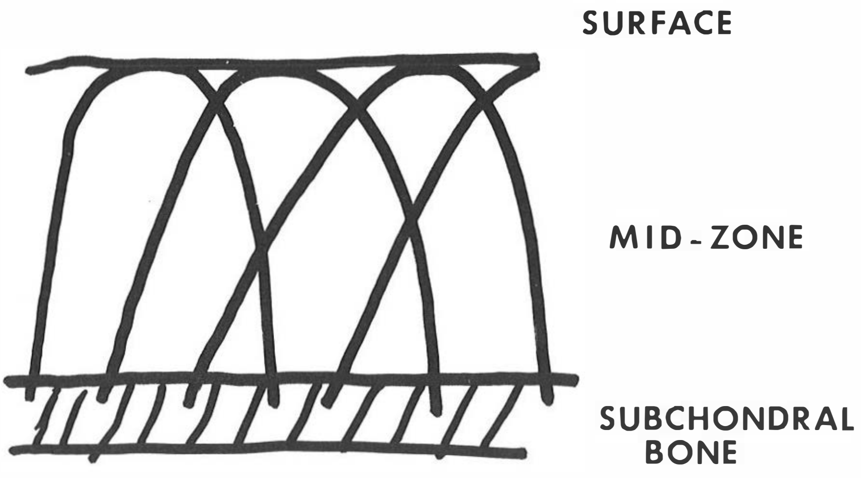
FIG. 5

Our trabecular map of the human patella shows that in the saggital view (fig. 3) the trabecular architecture runs normal to the surface, thus in and of itself being ideally oriented to resist bending and fracture from compression but very likely to transmit impulsive loads directly to the underlying articular cartilage. Viewed in the frontal plane (fig. 4) the trabecular architecture is more complex. It is basically vertical in its lateral upper two thirds, horizontal along its medial aspect and vertical along the crest. The distal part is an area of confluence from 3 directions of the various trabecular directions. It is precisely this area in which the mass of the trabecular orientation is not normal to the stress where the largest number of patellar fractures occur. The orientation suggests that in all liklyhood transverse fracture would begin on the medial side. More recent data from our laboratory measuring the relative stiffness (in 3 planes) of bony cubes taken from the various regions of the patella demonstrates that the distal region of the crest has the lowest transverse stiffness of all areas. The other parts of the patella were less compliant,which follows from the trabecular orientation. The trabeculae of the lateral and central crest regions are clearly vertical. Thus at right angles to the applied stress the confluence of the trabecular orientations at the proximal crest is not as aniostropic as is the distal crest, and furthermore resistance to complete transverse fracture would be provided by the proximal lateral trabecular orientation.

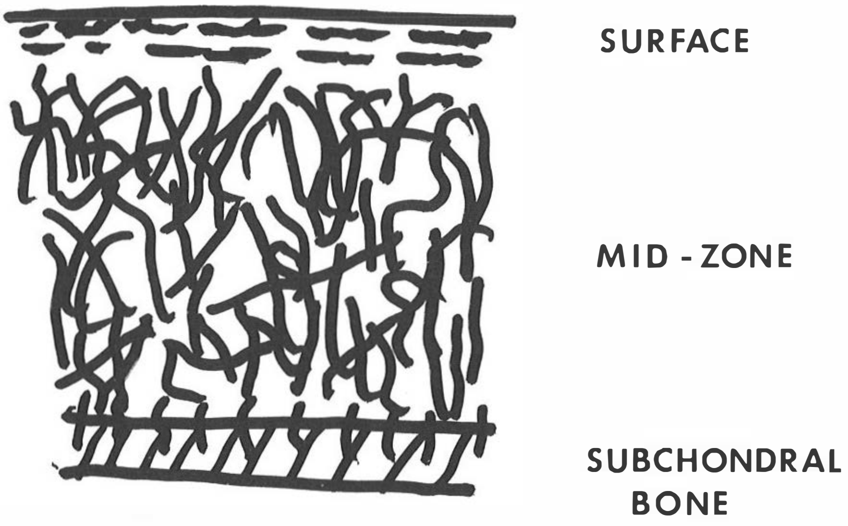
Comminuted fractures imply high velocity injuries. Unlike injuries at low strain rates the pattern of high velocity fractures does not depend on structure (Piekarski).

Chondral Fractures

Chondral fractures, that is injuries grossly limited to the cartilage, should not be confused with osteochondral fracture which are well discussed by



BENNINGHOF MODEL



ACTUAL

FIG. 6

But why are chondral fractures rare on bones other than the patella? Most joints are highly congruent and the general outlines of their load distribution are defined by their bony fit. The patello-femoral joint, by contrast, fits poorly. It depends upon the compliance of its relatively thick cartilage in order to maximize its load bearing area. The articular cartilage of the surface of the patella is the thickest of all the articular cartilage in the human body, approximating 6 millimeters. This is the maximum thickness that would still permit diffusion essential for the nutrition of the basilar chondrocytes. This means that at loading situations at extremely high strain rates, when the cartilage cannot compress and thus distribute the stress over a large area, stress concentrations will occur. This would promote the occurance of chondral fracture. Other joints in the body depend less completely upon deformation of cartilage to maintain large surface areas and are thus less susceptible to chondral fracture. The clinical experience bears this out.

Summary

The high incidence of chondral fracture of the patella can be explained by the areas of high stress concentration that would occur in high strain rates in the patello-femoral joint because of the heightened necessity for articular cartilage compression to maintain reasonable surface contact areas of that joint. The high incidence of fracture of the distal part of the patella is most probably the result of the relatively weakened overall organization of its trabecular structure in this area. The relatively increased incidence of transverse fractures, especially between the middle and distal thirds of the bone, can also be explained on the basis of trabecular orientation for this is a region of altered trabecular structure from a primarily vertical one into a substantially mixed and horizontal orientation of the trabecular sheets which is not as strong.

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References

McCall, J. (1969) Load Deformation Response of Microstructure of Articular Cartilage, Chapter 3 in Lubrication and Wear in Joints, ed. by V. Wright, Lippincott, Philadelphia.

Milgram, J.E. (1963) Osteochondral Fractures, Chapter 8 in Management of Internal Derangements of the Knee, ed. by A.J. Helfet, Lippincott, Philadelphia.

Piekarski, K. (1970) Fracture of Bone. J. Appl. Physics. 41:215-223.

Radin, E.L. and Paul, I.L. (1971) Importance of Bone in Sparing Articular Cartilage from Impact. Clin. Orthop. 78:342-344

Radin, E.L.; Paul, I.L. (1971) The Response of Joints to Impact Loading I. In Vitro Wear. Arth. Rheum. 14:356-62.

Radin, E.L.; Paul, I.L.; and Lowy, M. (1970) A Comparison of the Force Transmitting Properties of Subchondral Bone and Articular Cartilage. J.Bone Joint Surg. 52A:444-456.

Radin, E.L.; Paul, I.L.; and Pollock, D. (1970) Animal Joint Behavior Under Excessive Loading. Nature 226:554-555.

Scott, J.C. (1949) Fractures of the Patella. J.Bone Joint Surg. 31B:76-81