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INTRODUCTION TO JOINT BIOMECHANICS*

HAROLD M. FROST, M.D.**

The application of the knowledge and discipline of other scientific fields to medical fields seldom fails to bring new understanding and advance in the diagnosis, treatment, and prevention of disease. Such advance characterizes the application of mechanical engineering to anatomy and physiology. The result of this application is the field of biomechanics. Biomechanics is not limited to mechanics; overtones of physical chemistry, solid state physics, metallurgy and thermodynamics appear in the field and other overtones may be expected.

In this paper a way of thinking about joints is introduced which provides some insight into the development of phenomena previously obscure in origin. Orientation of future joint research along the lines suggested should increase the yield of such research. It is hoped that the paper will provide some stimulus for such work.

BEARING ANALYSIS APPLIED TO JOINTS

LUBRICATION

A. Lubricant: Synovial fluid is the joint lubricant. Synovial fluid possesses the properties of viscosity, surface tension, and adhesion to the surface of hyaline cartilage. These properties are due to submicroscopic characteristics of the synovial fluid, among them being the size, shape, density, charge concentration, pH, and interactions of the various molecules in the synovial fluid. From the standpoint of lubrication, the most important molecule in the synovial fluid is that of the mucin. Alterations in the submicroscopic characteristics produce grossly measurable changes in properties such as viscosity, surface tension, and refractive index.

A lubricant functions under one of two conditions: boundary layer or hydrodynamic.

B. Boundary Layer Lubrication: Two bearing surfaces slide slowly upon one another. A film of lubricant is present between the bearing surfaces. The lubricant film lowers the moving friction and decreases the wear that would be present if the bearing surfaces were dry. Ideally the lubricant is strongly adherent to the bearing surfaces, forming a very thin protective coating over the surfaces.* Some wear is always present under boundary layer conditions because there is always some contact of the moving surfaces. Boundary lubricants are usually greases of high viscosity and surface tensile strength. Under boundary conditions a load limit exists beyond which the lubricant is increasingly ineffective. (Figure 1.)

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**Department of Orthopedic Surgery.

*The adhesiveness of a lubricant is usually enhanced by adding small quantities of chemically corrosive substances to the body of the lubricant.
BOUNDARY LAYER LUBRICATION

In the top part of the figure one flat lubricated plate slides on another. In the bottom part of the figure the bearing surfaces are highly magnified and diagrammatic — the bearing surfaces are microscopically rough. As a result, most of the load is borne by small high spots, one of which is illustrated in the center of the figure. Lubricant fills the gaps between the bearing surfaces but is rubbed off where high spots touch.

A: Lubricant. B: Monolayer of molecules adherent to bearing surface. C: Bearing surface. D: High spots, or asperities. During motion the temperatures of the abrading high spots become high, often high enough to melt the microscopic hills. Bearing wear is appreciable under boundary layer conditions.
HYDRODYNAMIC LUBRICATION

A rotating journal is diagrammed in cross section at the top. A diagrammatic, enlarged section of this journal is depicted in the lower part of the figure and is equivalent to the function of a moving joint. Motion is from right to left, the bottom part of the bearing being stationary. A film of lubricant is pumped in from the right and is carried along by the moving surface. As the bearing surfaces approach closer the fluid pressure increases; its speed also increases. The bearing surfaces approach until the lubricant pressure equals the load on the bearing. At this point the bearing surfaces remain, moving neither closer nor farther apart. A change in load, or in bearing speed, or in lubricant viscosity, results in a corresponding change in the minimum lubricant film thickness in a bearing operating under hydrodynamic conditions.
A: Fixed part of the bearing, bearing backing. B: Babbitt or bearing material. C: Lubricant being forced in between moving bearing surfaces. D: Moving part of bearing: the shaft, in cross section. E: Minimum film thickness here. Under hydrodynamic conditions the minimum lubricant film thickness is always greater than the size of the largest microscopic surface irregularities on the bearing surface, so there is no touching of the bearing surfaces. As a result wear is infinitesimal. F: Lubricant is expressed from between the moving bearing surfaces, carrying away the frictional heat generated. In human joints and in machines this fluid is recirculated into the bearing again, but by different means. In machines motion is usually indirectional. In joints motion is oscillatory or reciprocal, and the lubricant expressed during, say, flexion of the knee, is returned by extension.

C. Hydrodynamic Lubrication: Two bearing surfaces move rapidly on each other. The lubricant, usually an oil, is pumped in between the moving surfaces under pressure. As a result, a film of lubricant forces and keeps the bearing surfaces apart. Under hydrodynamic conditions there is almost no wear and friction is reduced to a minimum. Heat is generated by the frictional resistance of the lubricant to shearing. (Figure 4). This heat must be carried away by conduction through the bearing material and/or by circulation and cooling of the lubricant. Otherwise the heat generated may damage both the lubricant and the bearing materials. This problem is more important in machines than in joints because in the latter the heat safety factor is large. Poor dissipation of frictional heat is not known as yet to cause joint damage. Some microscopic areas of heat damage could possibly occur in heavily loaded, severely osteoarthritic joints. (Figure 2.)

FRICTION

A. Dry Bearings: Friction is the resistance to moving one bearing surface on another under a load. In a dry bearing, starting friction is due to the contact and actual welding together of minute high spots — asperities — on the adjoining bearing surfaces. The force required to start the bearing moving is thus related to the tensile and shear strengths of the bearing material. Moving friction in a dry bearing is the work required to melt the minute high spots on the bearing surfaces as they impinge on one another and is thus related to the melting points of the bearing materials.

B. Lubricated Bearings: In lubricated bearings under boundary conditions some of the friction is due to contact (and thus wear) of the two bearing surfaces, and some is due to the viscosity of the lubricant. While heat is generated by both processes, it is smaller in amount than in dry bearings and usually produced at a slow rate so that heat dissipation is seldom a problem.

Under hydrodynamic conditions there is no contact of the bearing surfaces and thus no appreciable wear except during starts and stops. Heat is generated almost entirely from the viscosity of the lubricant which is sheared between the bearing surfaces. (Figure 4). This heat is considerable and unless dissipated in some manner, it will elevate temperatures sufficiently to damage the lubricant and the bearing.

C. Joints: In a normal human joint moving slowly and intermittently under load, boundary conditions exist. One can often detect the abrasion occurring during this condition as a fine crepitus under the slowly moving patella or as a self-audible grating when the neck is moved slowly in small increments.
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In normal human joints moving rapidly, hydrodynamic conditions exist and wear is reduced to an insignificant level by a thick film of synovial fluid forced in between the moving joint surfaces. The means by which synovial fluid is formed, pooled, circulated and pumped in between the moving joint surfaces are complex and at present imperfectly known. Knowledge of these factors will probably improve our understanding and treatment of arthritides to a large extent.

In abnormal joints, such as in chondromalacia, in a joint made irregular by fracture, or in severely osteoarthritic joints, the capacity of the lubricant to protect the joint surfaces from touching is exceeded, even under hydrodynamic conditions. Contact of the two surfaces occurs, large particles of the bearing surfaces are gouged or torn out of each surface during motion, and large amounts of heat are generated in physically small volumes of material. Wear is severe and rapid.

BEARING MATERIAL

The hyaline cartilage lining joints is comparable to the Babbitt of a machine bearing. (Figures 2, 3, 7). It must possess five properties to function well. Hyaline cartilage is a poor structural material and is not intended to provide structural strength or stability. It provides a low-friction, low-wear, self repairing gliding mechanism.

The requisite properties of a bearing material are smoothness, adhesion to the lubricant, absorption of the lubricant, resistance to shear greater than any shear which may be transmitted to the bearing by the lubricant under normal operating conditions, and sufficient surface area to carry the loads placed on the bearing.

A. Smoothness: Under the magnification of the electron microscope the apparently smooth surface of hyaline cartilage in a normal joint is resolved into jagged edges of bare collagen fibers projecting into the joint space. These high spots cause contact and some wear under boundary conditions in normal joints. Under hydrodynamic conditions the lubricant film is much thicker than the height of the largest surface protuberance and no contact or significant wear occurs. When surfaces are rough to the unaided eye the condition is already serious and wear is rapid. Surface smoothness is essential to minimize wear.

B. Adhesion: Physicochemical interaction between cartilage substance and the synovial fluid molecules is responsible for the fact that normally the two are quite adherent and it is difficult to “rub off” the mucin molecules from the cartilage. The nature of the forces responsible for this adhesion are such that relatively small disturbances in composition or physical characteristics could affect the adhesiveness considerably. At present there is no positive evidence that this occurs in man: it has not been sought for.

C. Absorption: The construction of the hyaline cartilage is such that the synovial fluid is absorbed by the cartilage. The cartilage “soaks up” some of the lubricant as a blotter soaks up ink. In situations where insufficient supply of lubricant is carried in between the joint surfaces this absorbed fluid may be squeezed out and act as a temporary supply.
Frost

D. Shear Strength: The hyaline cartilage covering joint surfaces is composed of bundles of collagen embedded in a cement substance, much as bundles of string might be embedded in gelatin. The collagen is strong, flexible, but not very elastic, while the cement substance is quite elastic but not strong. The collagen fibers come directly out of the subchondral bone and overlying calcified cartilage, course through the thickness of the cartilaginous covering on the subchondral bone and come to lie in largely tangential fashion at the joint surfaces. The cartilage is accordingly strongly attached to the subchondral bone and is strongly resistant to being plucked away from or sheared off from the subchondral bone. The feltwork of parallel fibers at the joint surface makes the cartilage difficult to split apart. (Figure 3). When this surface layer of tangential fibers is worn off, vertical splits may develop in the cartilage. This is the initial pathology in the condition known as chondromalacia.

Figure 3

Diagrammatic, enlarged longitudinal section of a joint. Layer (A) is hyaline cartilage; the joint cavity is at the top. The arching, dark lines represent the direction of collagen bundles. These bundles comprise a major part of hyaline cartilage. It will be seen that at the joint surface the bundles are tangential, but at the base they emerge radially to the joint surface. Layer (B) is the zone of calcified cartilage containing the lacunae of degenerating and degenerated chondrocytes. The upper surface of this layer is slightly irregular, the lower surface markedly so. These irregularities make it almost impossible to shear the layers apart (see Figure 5), under normal circumstances and in the presence of compressive load. Layer (C) is the subchondral bone containing an arched series of trabeculae which take load from the cartilage and distribute it to the metaphyseal cancellous bone.

The shear strength of hyaline cartilage is due to the collagen in the cartilage and under normal circumstances is more than sufficient. (Figures
Diagrammatic representation of behavior of a lubricant between moving bearing surfaces. The moving bearing surface is above (A), the fixed one below (B), and the direction of motion is as diagrammed. Lubricant enters from the right (C). A thin film of lubricant molecules adheres to each bearing surface (D) and remains attached thereto. Each successive layer of lubricant moves on the preceding layer of lubricant under the drag from the moving bearing surface. This moving of layers of lubricant on each other is shear; the drag, or fluid friction, is viscosity, or resistance to shear. A shearing force is transmitted from the lubricant to the bearing surfaces and is outlined by the magnifying glass. When enough shearing force is generated the bearing material (F) can be stripped from the bearing backing (B).

4, 5, 6). When surface roughness exists in the joint, however, the strength of the collagen may be exceeded and bits of cartilage plucked out of or shorn off from the subchondral bone during motion. In such a joint the heavier the load, the faster and more severe the wear and thus the greater the symptoms. It is for this reason that progressive resistance exercises are not the best prescription for the patient with patellar chondromalacia.

E. Bearing Area: The bearing area will be elaborated on next and deserves separate consideration.

**BEARING SHAPE**

From anatomy texts one might conclude that nature uses diverse bearing shapes having no common features. Nevertheless, it has been found that diarthrodial joints do have two design features in common that are not apparent at first glance but that are of considerable physiological significance.

A. **Fluid Wedge**: Under no-load conditions the diarthrodial joints do not have accurately mating surfaces. Their shape is such that there is a central, small area of contact* but at the periphery of the joint an open, wedge-shaped space exists. The gap in this wedge is usually filled with synovial fluid. When motion
The arrows (SF) represent a shearing force created by motion of the joint surfaces. The upper member of the joint and its motion are represented by arrow (M). The viscosity of the synovial fluid is responsible for transmission of shearing force from the moving joint surface to the stationary joint surface. If the cohesion of hyaline cartilage (A) to calcified cartilage (B), or of calcified cartilage (B) to subchondral bone (C), were inadequate then the shearing force which always accompanies joint motion would produce the shear failure and displacement shown.

occurs the volume of fluid in the wedge is carried between the moving surfaces and forces them apart, causing hydrodynamic conditions. The fluid wedge, adhering to the cartilage surface, and possessing a fair viscosity, is an essential part of the "pump" that, with the aid of motion, creates hydrodynamic lubrication of human joints. In extreme cases such as the knee, where the wedge at the joint periphery is large, a meniscus occupies the gap, maintains an unbroken fluid wedge, minimizes turbulence which would break the fluid wedge up, and is flexible enough to adapt to varying positions of the joint. (Figures 2, 7).

B. Variable Bearing Area: The elastic flexibility of the hyaline cartilage, subchondral and metaphyseal cancellous bone which support the hyaline cartilage, and metaphyseal cortex which supports the entire joint complex, is graduated.

The structures were listed in order of decreasing elasticity. (Figure 9). As a result of their elasticity the central area of closest contact in the resting, unloaded joint progressively enlarges as the load increases. In man, therefore, the surface area of the bearing is variable. The bearing area is dependent on

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*Contact does not necessarily mean touching. Usually a thin film of synovial fluid prevents actual contact over any significant area of the normal joint.
Now we diagram the deformation or strain produced in the hyaline cartilage, calcified cartilage and subchondral bone by the shearing force generated by joint motion. Compare with Figure 1. The shearing force causes the whole joint surface to give way to the left. The amount of strain is exaggerated, but some strain always occurs with the shearing force of joint motion.

and varied by changes in the load. This is a unique arrangement in bearings. (Figures 6, 8A, 8B).

BEARING BACKING

The hyaline cartilage covering the joint surfaces serves the functions of lubrication. Structurally it is too weak for any sizable load, just as the Babbitt in the bearings of a machine is too weak for any large load. Some backing or supporting structure must be provided. In man the bearing backing may be considered in three parts: the subchondral bone, metaphyseal cancellous bone, and metaphyseal cortex.

A. Subchondral bone: The subchondral bone microscopically is a nearly continuous but rather rough, thin plate of bone underlying the calcified cartilage at the base of the hyaline cartilage layer. The external roughness probably adds resistance to shear between the zone of calcified cartilage and the subchondral bone. The subchondral bone is quite flexible and must itself be supported. (Figure 3).

B. Metaphyseal Cancellous Bone: A system of trabecular archways originating on the under side of the subchondral cortex takes the compressive, tensile and

**All structural materials are elastic, differing only in the degree of elasticity. All structural materials yield under a load, no matter how small. The yield is known to the engineer as strain. Normal human bone and cartilage undergo considerable elastic strain in response to physiologic loads, a fact not apparent in the static view of the dissecting room.
A diagrammatic joint (A) Hyaline Cartilage; (B) Subchondral bone; (C) Metaphyseal cancellous bone — not diagrammed. At (D) a wedge-shaped space at the periphery of the joint exists and normally is filled with synovial fluid — the fluid wedge. At (E) the peripheral wedge shaped gap is so large that nature fills it with a filler — which is known anatomically as the meniscus. Under resting conditions or with small loads only the central area, (F) of the joint is actually bearing. The load at the bearing area is distributed by the subchondral cancellous bone in the manner diagrammed by the arrows.

shear loads transmitted to the subchondral cortex and distributes them to the widest possible area of the metaphyseal cortex. Some elastic flexibility is necessary for this function.

The elastic flexibility of the whole cartilage-metaphyseal bone complex has already been referred to as the mechanism responsible for the variable bearing area in man which is controlled by the load. This flexibility also aids in distributing and equalizing loads and in eliminating any local zone on the bearing surface which might carry too much load.

C. Cortex: The metaphyseal cortex, quite thin at the margin of a diarthrodial joint, gradually lessens in diameter, and thus cross section area, but increases in
The tibial side of the knee joint is seen as it would appear if one were looking down on it. The shaded areas at upper left represent the amount of bearing area in close apposition and bearing load at rest or with small loads. The majority of the joint surface is not bearing. In the lower part of the figure the peripheral wedge is illustrated for no-load or light load conditions as it would appear on a longitudinal section through the joint.

thickness as the diaphysis is approached. This is the final touch in the design of the joint mechanism and is the manner in which the apparently incompatible demands of mobility, adaptability, and structural stability are satisfied. Elasticity gradually tapers off from the joint surface to mid-diaphysis.*

D. One of the necessary properties of the bearing backing has been repeatedly referred to: Elasticity. Other properties are also needed for proper functioning of the bearing as a whole. These properties include sufficient strength, fatigue resistance, and heat dissipation. These are separate matters which need not be gone into in detail here.

SUMMARY OF BEARING THEORY APPLIED TO JOINTS

A series of requisite properties or materials will be listed separately, although they are often interdependent.

Lubricant: The synovial fluid must adhere to the bearing surfaces, be present in adequate supply and possess relatively constant viscosity and surface tension. The synovial fluid must meet the harsh demand of subserving both boundary layer and

*The energy absorbing capacity and damping capacity of the metaphyseal structures are also important functions but are not discussed.
The same as in 8A but now under heavy load. The shaded area in the upper left part of the figure again represents the bearing area and is seen to have enlarged considerably. In the lower part of the figure the arrows show, in longitudinal section through the joint, how the material in the metaphysis must be elastically displaced to permit increase in the bearing area under increase in load. It can be seen that failure to adjust bearing area to load could lead to severe overload on the small bearing area in Figure 8A under heavy load conditions. Any situation which produces an abnormal protuberance in the joint surface, or which reduced normal subchondral cancellous elastic flexibility can produce such overload and lead to degenerative arthritis.

hydrodynamic lubrication while simultaneously carrying nutrient materials to the cartilage for use by chondrocytes and carrying away catabolites. Wear and friction must be minimized and frictional heat must be carried away and dissipated.

**Bearing Surface:** This must be very smooth to minimize friction and wear. The maximum roughness must be of lesser order than the minimum thickness of the lubricant film.

**Absorption of Lubricant:** The bearing material should absorb some lubricant for use in occasional “dry” periods when lubricant is not being pumped in between the bearing surfaces.

**Lubricant Pump:** A mechanism is required to force synovial fluid in between the moving joint surfaces. This “pump” arises from a combination of circumstances: the relatively high viscosity of the synovial fluid, its high adhesiveness to the joint surfaces, the fluid wedge at the periphery of the diarthrodial joints, and the oscillatory rather than continuous nature of joint motion, so that lubricant expressed from between the joint surfaces is returned by the next motion, which must be in the opposite direction. In some joints there is also an arrangement of tendon and muscle such that surplus
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synovial fluid in the joint recesses is forced into the middle of the joint by muscle action, ensuring that the synovial fluid does not pool uselessly.

Figure 9

Stress (resistance to applied force or load) plotted against strain (deformation or giving away), diagrammatic. Comparison of qualities of cortical bone (A), cancellous bone (B), and hyaline cartilage (C).

Variable Bearing Area: This is produced by elastic flexibility of the tissues composing the joint. The flexibility is tapered, being maximal in the bearing material and minimal in the diaphysis. The resulting elastic flexibility is such that the load placed across a joint determines the bearing area of the joint. The bearing area is minimal at rest and maximal at high load. For any given set of bearing conditions there is an optimum bearing size, and varying the load on the bearing varies the optimum bearing area similarly. Our joints have engineered into them the capacity to make instantaneous selection of the best compromise between the conflicting requirements of wear minimization and load carrying capacity.
Figure 10a
AP and lateral views of left knee of a 60 year old man with osteopetrosis. Marked narrowing of the patellofemoral and medial tibiofemoral joints are seen. There are large osteophytes at the medial joint margin.

Figure 10b
Clinically there is much crepitus but minor symptoms. The opposite knee is similarly affected clinically and roentgenographically. This is an unusual cause of alteration in the elasticity of the joint-metaphyseal complex mentioned in the text.

Figure 11
AP x-ray view of ankle of 34 year old woman. Ankle pain, warmth, tenderness and limitation of active and passive motion for 3 mos. Diagnosis of rheumatoid arthritis substantiated by the usual tests, by involvement of other joints subsequently, and by subsequent course.
There is marked narrowing of the tibiotalar joint. This narrowing is due to wear, not to pannus. The wear in turn results from a disturbance in the synovial fluid, the hyaline cartilage, or both. The disturbance must be such that lubricating efficiency is lowered.
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The elastic flexibility of hyaline cartilage should depend in part on the metabolic activity of the chondrocytes buried in it, and so in turn on the various local and systemic factors which might affect the chondrocyte metabolism. It should depend also on the factors affecting the synovial fluid.

The elastic flexibility of the bone which forms the backing to the cartilage must depend on blood supply, trauma, neoplasm, and other factors, some of which probably have not yet been recognized, in addition to the known local and systemic factors which affect osteoblastic activity. Too much bone backing up the cartilage would make the bearing mechanism too rigid, while too little would make it too flexible.

Strength of cartilage, subchondral bone and their mutual bonds: During an active life large tensile, compressive and shear stresses are developed in the various components of joints which have been discussed. Under normal conditions the strength of the materials is sufficient to prevent failure under isolated loads. Under abnormal conditions, however, failure may occur. For example, in chondromalacia pieces of cartilage are plucked off from the subchondral bone, and in osteoarthritis pieces of bone are sheared off or plucked out of the main body of the joint.

Fatigue limit of joint tissues: We are just beginning to appreciate that living tissues experience fatigue in the sense used by structural engineers. Collagen fibers may fail after a certain number of cyclic applications of load, as may bone trabeculae, or islands of extra-Haversian bone, or whole bones. March fractures, spontaneous heel cord ruptures and Looser's zones are specific examples of gross fatigue failures, while microscopic cracks in living bone are an example of microscopic fatigue failures. The fatigue limit of joint tissues becomes a problem when protective and repair mechanisms are impaired, as in neuropathic joints.

Self repairing feature of joints: The structural materials of which joints are made are alive and possess the capacity to repair themselves. Nature has made good use of this capacity. The various parts of a joint are designed for a limited lifetime, which does not approach the lifetime of the whole organism. The Engineer apparently decided that, rather than make joints very large, very strong, and very durable so that they would last three score and ten, he would make them light, streamlined, and with parts designed for a few years only. He added to this a continuous replacement of worn material as it develops. Both cartilage and bone wear and/or fatigue and both are replaced or repaired by various mechanisms during life. Retardation of this normal repair process leads in turn to cumulatively evident joint disease just as surely as acceleration of wear does so.

DISCUSSION

We may now consider briefly some situations which may be explainable by the foregoing material.

A. Alteration in synovial fluid quality: It is well known that in many cases of rheumatoid arthritis the first x-ray sign is a remarkably even narrowing of the affected joint spaces. This is seen before the manifestation of destruction, marginal notching, or the appearance of pannus. The narrowing of the joint space is due to wearing away of the cartilaginous surfaces. This in turn must be
due to loss of lubricating efficiency. Since it is not due to roughness of the joint or pannus, it must be loss of lubricity of the synovial fluid or loss of elasticity of the hyaline cartilage cement substance or both that is responsible.

A similar situation occurs occasionally in cases of epiphyseolisthesis. In the cases being considered the joint space melts away on x-ray. This loss of joint space is not related to treatment, function, or degree or slip, and so must be due to a disturbance in the quality of the lubricant, or the quality of the hyaline cartilage or both.

B. Loss of the fluid wedge: It is known that many years following meniscectomy a degenerative arthritis may appear and that the presence of detectable joint damage at the time of arthrotomy is not necessary for it to develop. It has been suggested, and the writer agrees, that the likely cause is failure of an adequate meniscus to regenerate after surgery, and so loss of the normal fluid wedge* which assures hydrodynamic lubricating conditions. The answer would seem to be to remove enough of the original meniscus so that a raw rim is produced which can regenerate a new meniscus.

C. Roughness of the joint surfaces: Familiarity with this situation is such that little need be said about it. Even the slightest step-off or irregularity in a joint surface following a fracture may be sufficient to cause severe wear and result in traumatic arthritis. Treatment should be designed to prevent or correct step-off from fractures that enter joints.

F. Alteration in subchondral elasticity: When too much bone in the subchondral area of a joint occurs, the elasticity of this area is markedly reduced. The overlying bearing surfaces will be overloaded under heavy loads, taxing the capacity of the bearing complex. Excessive wear may result leading first to a chondromalacia, then to a degenerative arthritis. A case is illustrated in which the cause of the excess metaphyseal bone is Osteopetrosis. Clinically there is severe tibiofemoral chondromalacia, but almost no patello-femoral chondromalacia.

Similar examples may be found when other lesions inducing appreciable osteoblastic response (such as osteomyelitis, or healing comminuted fractures) occur in metaphyseal bone close to a joint surface.

G. Insufficient bearing area: When part of a joint’s bearing area is lost, as by depressed fracture, or when genu varum follows malunion of a femoral shaft fracture, the result is that too much load is placed on a restricted bearing area. Rapid wear results and may lead to a degenerative arthritis.

CONCLUSION

Enough. Many more possibilities could be considered and debated. The paper has served its purpose if it starts the reader thinking about joints and their diseases in terms of bearings as well as (not instead of) living tissue. It has doubly served its purpose if

*The loss is caused by a marked local increase in turbulence, in theory at least.
someone has been stimulated to test the functional model outlined. A mechanical engineer’s view of joint physiology will not supplant the physiologist’s view, but it should complement it. From the brief examples given, it can be seen that the model does explain some phenomena otherwise difficult to understand.

**GLOSSARY**

**Bearing:** The complex of the lubricant between two moving bearing surfaces, the bearing surfaces, the bearing backing, and any associated structures.

**Elasticity:** The ability to deform or yield under load and to return to the original dimensions and shape after removal of the load.

**Fatigue:** The gradual onset of failure of a part subjected to repeated loads, none of which exceed the design limits of the structural material in question. Microscopic cracks appear in a material that is developing a fatigue failure. The cracks gradually grow until so little material remains intact that a single, minor load may lead to complete failure. Some materials are very sensitive to fatigue, others insensitive. Fatigue is influenced by corrosion, composition of the material, heat treatment, work hardening, nicks, scratches, notches, manner of clamping and other factors.

**Friction:** The resistance to motion of two bearing surfaces being moved on each other. **Starting friction:** The force required to begin motion of two bearing surfaces at rest. Starting friction is always larger than **moving friction,** which is the force required to continue motion once started.

**Load:** force or weight applied to a part.

**Lubricant:** A substance designed to decrease wear and lower starting and moving friction. Lubricants are usually liquids but in special circumstances may be gases or solids. The design of lubricants is an extensive and highly specialized field. A lubricant must be designed for each combination of unit bearing load, bearing speed, bearing and lubricant temperature, bearing material, rate and manner of lubricant circulation, rate of heat dissipation, physical and chemical environment.

**Strain:** The deformation of a material under load. The stretching of a rubber band is strain; the force required to strain (stretch) it = load.

**Stress:** The resistance developed in the interior of a substance in response to an applied load. There are three general types of stress. **Tensile stress** is a pulling apart. **Compressive stress** is a pushing together. **Shear stress** is a resistance to sliding of one surface on another, for example, a brick over the top of a table.

**Surface tension:** The force in a thin film or at the surface of a substance which acts to contain it. It is usually measured by an instrument which makes a film and then measures the force required to break the film.
**Frost**

*Viscosity*: Fluid friction. The lubricant between two bearing surfaces is subjected to shearing stress when the bearing surfaces are moving. The shearing stress is the resistance to being sheared, and is experienced by the engine turning the shaft of the bearing as lost work. The work done on the lubricant is converted to heat in the lubricant. Some of this heat is transmitted to the bearing surface, the remainder is carried away by the circulating lubricant. If the heat dissipating means fails, overheating will occur with damage to both bearing and lubricant. As the load on the bearing increases, or as the speed of motion of one surface on the other increases, an increasing amount of shear load is transferred to the bearing material because of the viscosity of the lubricant. If improperly designed, this shear load may strip the bearing off the backing material, leading to failure of the bearing.