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DISCUSSION

L. Sokoloff[14]

The medical profession has much reason to be grateful to engineers for their interest in the biomechanics and lubrication of joints. Mechanical theory has been applied to postural mechanisms since the time of Galileo and some fair information has been obtained about the forces acting on joints from conventional anatomical statics. Only within the past three decades has attention been given the mechanisms of lubrication, a problem of clinical interest because it may relate to the wear and tear of joints and the development of various types of arthritis to which we are all subject.

Most of the studies in the medical literature have been concerned with the rheological properties of synovial fluid, the fluid that lies within the space between the cartilages which are the bearing surfaces of the joints. The fluid has been the focus of these studies because it is easy to work with and is obviously viscous. Intuitively, the assumptions have been that the viscosity in some manner accounts for the lubrication of the joints. Elegant chemical analyses have established the basis for the flow properties of the synovial fluid, but it is now clear that the assumptions that the low friction of joints rests on these rheological characteristics are oversimplified and unrealistic.

A certain naiveté about how joints get lubricated has not been confined to physicians. The studies of Linn, McCutchen, Wilkins, and Radin have revolutionized our way of thinking. They have accomplished this by coming to grips directly with measurements of the friction of joints rather than confining themselves to speculations based on oversimplified theoretical models. Briefly summarized, their studies have demonstrated:

1 The friction of joint cartilage is low even when there is no synovial lubricating fluid. In other words, cartilages are intrinsically slippery bearings.

2 Synovial fluid provides an adjuvant lubricating action—but as the present paper shows, only if the bearing is soft, deformable and elastic.

3 The viscosity of the synovial fluid is not related measurably to the lubricating properties.

4 The lubricating ability of synovial fluid depends on its ability to adhere tenaciously to the joint surfaces.

I shall confine my remarks to physiological basis for the role of the cartilage in these phenomena.

The tissues of living things consist of minute units called cells. Joint cartilage is distinguished from other parts of the body in having relatively few cells. For the present purposes, it may be considered a water-rich matrix; 80 percent of cartilage is water. The matrix is a two-phase material. One component is a strong and inextensible fibrous protein called collagen. It is arranged in a fine network. The other phase is called ground substance. It is a highly viscous colloid solution that fills in the spaces between the fibers. The colloids are a complex group of polyanionic protein-polysaccharides. These materials contain a great deal of sulfate and so are strongly electronegative.

When the same microscopic section is viewed under polarized light, the matrix no longer looks homogeneous. Instead rather brilliant fibers are seen oriented in different directions. These represent the network of collagen.

When a static compressive load is applied to cartilage, there is an immediate deformity, that is followed by a prolonged creep. When the load is removed, there is a restitution toward the initial condition. The deformability of the cartilage is greatly influenced by the ionic environment in which it finds itself. Here we see that immersion of the cartilage in a highly concentrated solution of salts increases the deformability of the joint surface. Conversely, when the salts are washed out by conducting the tests in distilled water, the cartilage becomes very stiff, and the amount of deformation is reduced.

This sort of response of the cartilage to the ionic environment is strong evidence that the charge density of the ground substance itself is osmotically active in holding onto the matrix water in relation to the mechanical properties of the tissue. Washing out the cations in this circumstance uncovered the negative charges of the fixed sulfate groups of the protein-polysaccharide or PPS; and through their mutual repulsion, the stiffness of the colloid chains was increased. Addition of cations had the opposite effect.

Because the viscous protein-polysaccharides are trapped in a network of collagen, their osmotic pressure serves to keep the collagen inflated. The resulting tautness of the fibrous structure plus the relative bulk incompressibility of the whole mass serves as the basis for the immediate springlike elasticity of the cartilage. In addition, when the load applied to the cartilage exceeds the osmotic pressure, fluid exudes from the ground substance. This constitutes the creep phase of the deformation. The obverse takes place when the load is removed.

These data are consistent with the hypothesis that cartilages are lubricated, in the absence of synovial mucin, by a self-pressurized hydrostatic mechanism.

Engineering and medical professions may have somewhat different goals in looking at the problems of biological lubrication. One can envision drawing on some of God's wisdom in endowing joints with such low friction for application to man-made systems. Hopefully this might include development of orthopedic prostheses for joints. However, as a pathologist concerned with how joints work and fail, I take the liberty of suggesting several problems where engineers could be of great assistance:

1 No one has so far actually measured the stresses on animal joints and one would think that this is within the capabilities of present-day technology.

2 We don't have general understandings of why joints are structured the way they are. Why are the cartilages thick in certain regions, thin in others? What parts of the surface are in contact with each other when the joints are in use? And so forth . . . .

3 The lubricating ability of synovial fluid in various physiological and disease states should be measured.

4 The wear properties of cartilage should be measured as a function of age and disease.

These goals seem entirely realistic if engineers and biomedical workers could collaborate on them. We live in a world that is as wonderful as it is crazy. I pray that somehow the crazy part will get out of the way and let these wonderful opportunities become fulfilled.

Author's Closure

Dr. Sokoloff's discussion is welcomed by engineers, since it helps us to better understand the needs of the medical profession.

His suggested future studies are good; however, some work has already been done. Relative to the stresses on animal joints, I am not too certain what he means. If it is shearing stress, this was measured and reported in reference [13]. It resulted in determining a modulus of elasticity in shear of 127 psi. If it is average compressive stress, this has been reported by a few authors whose data resulted in the modulus of elasticity in compression ranging from 100 to 500 psi [13, 17, 22]. If it is the maximum load normally applied to a joint there is considerable

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literature. One reference is reference [16][15] in reference [13] of this paper. It gives the load at all positions of posture including the maximum load on the ankle of an average man weighing 150 pounds as being about 600 pounds when walking at the rate of 3 miles per hour. If the loaded area of the ankle is one square inch, the maximum average loading stress will be 600 psi. The peak loading stress probably would be within 10 or 20 percent of this value since the cartilage deformation is relatively large so the load distribution will be comparatively uniform.

Although most tests with synovial fluid were conducted with bovine synovia, because it was readily available, a few tests were conducted with human synovia with comparable low friction results.[16]

In the study of how joints work and fail the principal goal should be the determination of the causes and cures of the various forms of arthritis. For such a study it would be advisable to have a team with at least one person who has a good background in protein chemistry, since the chemistry of the body, to a large extent, controls its vigor. An arthrotripsometer should be one of the many tools used for the evaluation and solution of the problems which may arise during this study.

[15] Morton, D. J., and Fuller, D. D., *Human Locomotion and Body Form*, The Williams and Wilkins Co., Baltimore, Md., 1952, p. 178.

[16] Linn, F. C., and Radin, E. L., "Lubrication of Animal Joints. III—The Effect of Certain Chemical Alterations of the Cartilage and Lubricant," *Arthritis & Rheumatism*, Vol. 11, Oct. 1968, pp. 674–682.