

DISCUSSION

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In this paper the authors have successfully contrasted the bearing performance of normal and artificial joints in vivo and in vitro. Their discussion makes amply clear that animal joint lubrication is quite complex and very different from those of artificial joints. Indeed, the modes of animal joint lubrication are a matter of conjecture and speculation. Presumably the fortunate efficacy of normal joints to bear loads and protect the articular surface is the manifestation of the mechanical and physical properties of articular cartilage and synovial fluid. The mechanical and physical properties of prosthetic joint material, metal-on-metal and metal-on-plastic, are markedly different from those of the natural system. It is therefore not surprising that distinct modes of lubrication exist between the surfaces of these bearings. The present discussion concerns some basic questions arising from the dynamic interaction of articular cartilage and synovial fluid which may be important in the understanding of animal joint lubrication.

Recently many investigators have been reporting on the mechanical and physical properties of articular cartilage. The following properties are known about articular cartilage: (a) articular cartilage is a highly porous material of extremely low permeability [49]; (b) articular cartilage is not smooth [50]; (c) articular cartilage is a composite material composed of collagen fibers of various diameters and ultrastructure with interfibrillar spaces filled with fluid and amorphous ground substances [51]; (d) articular cartilage is viscoelastic with a salient creep and recovery behavior approximated by a viscoelastic simple body [52]; and (e) articular cartilage is a material where mechanical, physical and surface properties vary from site to site, joint to joint and whose tissue properties are strongly influenced by the state of the health of the joint as a whole. Also, investigators have attempted to characterize the rheological properties of the joint fluid. They have shown that: (a) synovial fluid is viscoelastic, although detailed attempts at characterization of the relaxation spectrum are sketchy and quantitative data is lacking [53]; (b) synovial fluid is nonlinear, since it exhibits a normal stress effect [54]; (c) the whole fluid contains a very important polymer called hyaluronic acid, although the conformational properties of these molecules have yet to be determined; (d) hyaluronic acid may be adsorbed on the surface of cartilage thereby providing a suitable protective layer during articulation [55]; and (e) the properties and quantity of the fluid are strongly influenced by the pathological state of the joint. These bearing materials are utilized in the synovial joints with variable kinematic conditions, geometries, and loadings. Such is the problem: the understanding of animal joint lubrication must necessarily consider these parameters under realistic physiological situations.

Upon closer scrutiny the current state of knowledge of some aspects of material property appears to be insufficient and physiologically inappropriate in explaining the experimentally observed phenomenon. As an example, two of the popular theories on joint lubrication take into account the porous nature of articular cartilage. These are commonly known as weeping lubrication as proposed by C. W. McCutchen [56]:

"Cartilage, as we all know, feels damp, and no amount of wiping dry will destroy its dampness. A sodden sponge also feels damp. Perhaps cartilage is a sodden sponge. . . . Imagine that two of these liquid-containing sponges are pushed together. We shall assume that their solid skeletons, or matrices, are weak in compression. When they meet, therefore, each matrix will tend to push the other back into the liquid with which it is soaked. Because each matrix has volume, such a pushing back would displace liquid towards the rubbing surface. . . . Since the matrices have been assumed to be limber, and since they are only very slightly compressed, they can support but little of the load. If they do not provide support, what does? The answer is that the load is carried by the hydrostatic pressure of the liquid, and therefore generates no friction."

and boosted lubrication as proposed by D. Dowson, et al. [57]:

"We have proposed a lubrication mechanism known as 'boosted lubrication' to account for the observed behavior of human joints under load. . . . When the cartilage surfaces approach each other contact will take place between the peaks on opposite surfaces. As the surfaces are pressed closer together the area of contact between the elastic cartilage will increase and in due course an appreciable part of the load will be accommodated by this contact. This implies that pools of trapped synovial fluid will form in the valleys and the hydrodynamic pressured generated in these pools by the approach of the surfaces will initially carry a substantial part of the applied load. In due course some of the pressurized fluid will escape directly or through the porous cartilage to low pressure regions surrounding the load-carrying area and an increasing percentage of the load will be carried by direct cartilage contact. The synovial fluid in the trapped pools will be enriched in the sense that the concentration of the large hyaluronic acid molecules will increase owing to the ready escape of the low viscosity constituent of synovial fluid along the film and through the cartilage pores."

Thus these cursive views of animal joint lubrication seem to indicate that the proposed two modes of joint lubrication appear to be mutually exclusive. The motion of fluid relative to the matrix must be the result of their rheological properties. A fundamentally different approach to the study of synovial joint lubrication would be to model the constituents of the synovial joint with appropriate rheological equations subjected to realistic physiological geometric and dynamic conditions. In an attempt to reconcile the differences between weeping lubrication and boosted lubrication, F. F. Ling [58] recently proposed a new model for articular cartilage. This model is based upon known numbers 49-60 in brackets designate additional references at end of paper.

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2 Numbers 49-60 in brackets designate Additional References at end of paper.
mechanical and physical properties as well as, recently observed ultrastructural information from the scanning electron microscope [50]. Fig. 13 may depict an asperity of the articular cartilage in a squeeze film situation. The parametric solution for the pressure as a function of \( r \) is plotted in Figs. 14 and 15. Here \( \varphi \) is the pressure in articular cartilage and \( \Phi \) is the pressure in the fluid. The flow across the surface of articular cartilage is proportional to \( \varphi - \Phi \). Initially the fluid is imbied by the cartilage in the central portion of the contact zone and exuded near the periphery. As the squeeze action progresses the fluid is eauded across the contacting surface. This process continues until an asymptotic state of self-pressurized hydrostatic mode is obtained. This result seems to indicate that there is a circulation of fluid during a simple squeeze film configuration and that the postulated modes of lubrication are manifestations of the material properties. In the opinion of this discussor, the postulation of lubrication mechanisms within animal joints has the role of serving to identify possible alternatives. The testing and verification of these hypotheses may lead to the understanding of the true nature of this problem.

The second basic question concerns the description and determination of physical and mechanical properties of articular cartilage and synovial fluid. The authors mentioned a number of things which are of importance. They quote a modulus of elasticity of 120 and 75 kg/cm\(^2\) for short- and long-term loading. Since articular cartilage is viscoelastic [60], such a statement is unclear. If the rheological model for articular cartilage is an elastic body, then the modulus of elasticity is meaningful and the time factor is not. If the time factor is meaningful then the meaning of the modulus of elasticity is ambiguous. Permeability and porosity are other important properties. Thus far quantitative data on these properties are sketchy. Further a possibility exists that some of this information may not be used to infer an in vivo mechanism of lubrication, since such information is obtained in vitro experiments under loading conditions different from physiological situations. In conclusion since there is much more to be done in the determination of material properties and testing and verifying of generalizations and hypothetical situations concerning modes of lubrication of animal joints, the subject will continue to be interesting and challenging.

Additional References


Authors' Closure

Dr. Mow is to be thanked for providing a thorough and interesting discussion. In describing a mechanism of lubrication whereby fluid can in different locations flow out of or into the surface of cartilage, the discussor has helped to reconcile two previously opposing views. It is likely that new ideas such as this, and the present studies on the surface of cartilage, will lead to even further understandings not only of lubrication, but of the likely way in which cartilage breaks down in osteoarthrosis. The role of the hyaluronic acid component of synovial fluid is not fully clarified, and the breakdown of cartilage could be due to lubrication failure, to failure of the material as a whole, or to other primary reasons.