DISCUSSION

F. C. Linn[2]

It is commendable for a physical scientist, like Dr. Mow, to study literature in the field of biology and give us the benefit of his work. Unfortunately, the literature reviewed is only a part of that available and in some instances the data are misleading.

A Thesaurus of Rheumatology [66][3] and the monthly publication of the Index of Rheumatology [67] gives a good coverage of the literature. One good criteria to use as to whether the data are of value is to determine whether or not the experiments on articular cartilage were performed dry or submerged in a physiological solution. To illustrate, most authors in the medical literature refer to cartilage as nonelastic; however, Sokoloff [68] found that submerged cartilage is elastic and tests on nonsubmerged cartilage is not elastic. But by adding a drop of fluid to deformed surface it returned to its original state immediately, indicating that the elasticity of articular cartilage is fluid dependent. Dr. Mow recognizes this. However, some of his references do not.

There are a few additional points that I will discuss to either expand or clarify this fine paper.

1 Under subtitle "Anatomy of a Synovial Joint," the author refers to cartilage as a "porous material." Gersh and Catchpole [69] are of the opinion that the fluid in articular cartilage is chemically bound, like in a jell, and not held in pores, like in a sponge. Whichever mechanism is employed by cartilage to hold fluid is of little moment for joint lubrication since in either case fluid flows within or is expelled from the cartilage by the application of an external force.

2 Under the subtitle "Synovial Fluid," references made to 570 psi as the maximum pressure for a man of 175 lb, between the first metatarsal and its sesamoid when standing on his toes. A 150-lb man will have a loading of at least 1000 psi between the patella (knee cap) and the knee joint when supporting all his weight on one leg when in a deep squat. When performing the "Russian dance" this value should be much higher. This point is raised to have engineers and physical scientists appreciate that the loads carried on joints, relative to their size, are quite high. However, the length of time such loads are carried is relatively short.

3 Under the subtitle "Cartilage," the author states that the dry weight of cartilage ranges from 25 to 40 percent of its wet weight. These data are found extensively in the medical literature, but apply to rib cartilage. Rib cartilage is easily obtainable and convenient to work with, so some investigators, not recognizing that cartilage varied depending upon its application, gave data for cartilage based on their investigations using rib cartilage. The 25 percent figure is for youth and it increases gradually to 40 percent at age 25 to 30 and remains constant for the remainder of life. The dry weight of articular cartilage is about 18 percent of its wet weight in youth and increases to 22 percent at about 25 or 30 years of age [67] and remains constant thereafter.

4 Under conclusions, the author suggests that synovial joints be studied to determine "the modes of lubrication existing within synovial joints." In addition to the five items suggested by the author, I would suggest that self-induced hydrostatic pressure be added. He also suggests that utilization of the principles used by "natures synovial joints" may be beneficial to man in designs of bearing for prosthetic devices. With this I agree and there may be many applications for bearings designed utilizing these principles.

I recommend that more investigators carry on experimental work utilizing animal joints and that they design their equipment to obtain instantaneous data at every point in a cycle of operation. I further suggest that they will find an extremely complex problem and many more facets to investigate than proposed to date. To those who undertake such investigations, may they have the fortitude to come up with answers so as to relieve or eliminate the suffering of millions of people from the scourge of arthritis.

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[3] Numbers in brackets designate Additional References at end of Discussion.

Additional References

66 Ruhl, M. J., and Sokoloff, L., "A Thesaurus of Rheumatology," *Arthritis and Rheumatism*, Grune and Stratton, Inc., New York, Vol. 8, No. 1, Part II, Feb. 1965.

67 *Index of Rheumatology*, American Rheumatism Association, New York.

68 Sokoloff, L., "Elasticity of Aging Cartilage," *Federation Proceedings*, Vol. 25, May-June 1966, p. 1095.

69 Gersh, I., and Catchpole, H. R., "The Nature of Ground Substance of Connective Tissue," *Perspectives in Biology and Medicine*, Vol. 3, 1959–1960, pp. 282–317.

70 Linn, F. C., and Sokoloff, L., "Movement and Composition of Interstitial Fluid of Cartilage," *Arthritis and Rheumatism*, Vol. 8, 1965, pp. 481–494.

Author's Closure

The author wishes to thank Mr. F. C. Linn for some of his worthwhile and elucidatory comments. In particular items 2 and 3 were very much appreciated. However the author feels that the discusser missed the spirit of the article and hence he will take this opportunity to clarify this situation.

First of all it was not the intention of the author to write a compendium on the subject of synovial joints. Simply, the intent was to present relevant facts pertaining to the mechanical properties of the constituents and possible ways of describing them. Secondly, in regards to comment 1, it seems that at present there is indeed much confusion concerning the porous nature of the cartilage. To verify this statement I would like to quote from the discussor's own paper [29]:

> "The flow rate of the fluid through the colloid matrix must be governed by a number of factors: the cross sectional area, continuity and direction (isotropism) of the 'pores' of the matrix..."
>
> "The viscoelastic properties of the matrix, including collagen, may also contribute to the flow rate by affecting the pore size."

However, since the approach is phenomenological, the exact nature of the pores, or in general the microscopic structure, is of no importance. This is a fundamental assumption, which one accepts, and is universal to all studies in elasticity, fluid mechanics, etc.

Finally the problem suggested by Mr. Linn in his item 4 is just an example of that suggested by the author's item 5. To wit, consider a layered half space. The top layer is defined by a fluid-filled poro-elastic medium. This phenomenologically describes the behavior of cartilage. The lower half space representing the impervious bone is characterized by an elastic medium. To simulate the reciprocating nature of the motion found within diathrodial joints, the following boundary conditions may be imposed:

$$p^0 = \tau(x)e^{-i\omega t} \qquad y = 0$$
$$\sigma_{iy}{}^c = 0$$

where $y = 0$ defines the free surface of the cartilage. Here p^0 is the pore pressure on the surface of the cartilage, $\tau(x)$ is an integrable function, $\sigma_{ij}{}^c$ is the stress tensor of the elastic matrix of the poro-elastic layer, and ω is a typical frequency of joint motion. The governing equations of the poro-elastic layer subjected to these boundary conditions constitute a particular squeeze film problem. If the solution of this squeeze film problem shows that there is a build up of pore pressure in the poro-elastic layer then the postulated "self-induced hydrostatic pressure" will exist in the cartilage. Hence we see that "self-induced hydrostatic pressure" is a result of more fundamental considerations. To this end, the recent investigation of M. C. Mow and F. F. Ling[4] shows that for steadily moving arbitrary loads on the above mentioned system, the poro-elastic medium is capable of sustaining a large hydrostatic pressure within the layer.

[4] Mow, M. C., and Ling, F. F., "On Weeping Lubrication Theory," PhD thesis, Rensselaer Polytechnic Institute, Troy, N. Y., 1968 (to appear in *ZAMP*).