

Response to Comment by Charles W. McCutchen

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We thank Dr. McCutchen for his comment. We are keenly aware of his hypotheses for cartilage lubrication [1,2] and agree with one of the fundamental premises he first proposed, namely that hydrostatic pressurization of the interstitial fluid of cartilage supports most of the contact load transmitted across articular surfaces, thereby reducing the interfacial frictional force exerted on the solid matrix of the opposing surfaces. We have previously formulated a cartilage friction model [3,4], within the frameworks of the biphasic [5] and triphasic [6] theories of cartilage, to quantify this mechanism, and we have recently found excellent agreement between the model predictions and experimental data [7], thus supporting Dr. McCutchen's original hypothesis.

In our model, the direction of interstitial fluid flow at the contact interface is irrelevant to the mechanism of friction reduction by interstitial fluid load support. The only relevant issue is the magnitude and duration of interstitial fluid pressurization. Our recent experimental studies confirm that this pressurization can last for hundreds of seconds or longer [7,8]. From our perspective, it is thus inconsequential whether the interstitial fluid "weeps" out of the tissue or is "boosted" into it. It is only because the direction of flow had been debated historically in the literature that we referred to it in our discussion.

We respectfully disagree with Dr. McCutchen's statement that "Were [weeping flow] not present cartilage would be, in effect, an impervious bearing . . ." Cartilage is a highly porous tissue, particularly near the articular surface where the porosity can approach 90% [9,10]. As demonstrated in our model [3], it is not necessary for a layer of fluid to separate the articular surfaces in

order for its lubrication to be effective. When two cartilage layers come into contact, each with a surface porosity of 90% (or solid fractional content $\varphi^s = 0.1$), a fraction of $1 - (\varphi^s)^2$, or 99%, of the apparent contact area consists of fluid-against-fluid or fluid-against-solid contact. Since the fluid is typically highly pressurized under loading, due to the relatively low modulus and permeability of cartilage, most of the contact load at the interface will be supported by fluid, producing negligible friction. Only 1% of the contact area will consist of solid-against-solid contact, where friction occurs. Trapped lubricant pools would further decrease solid-against-solid contact, and thus frictional forces. Thus, even in the absence of weeping flow, our model predicts that the porous nature of cartilage will maintain effective lubrication.

References

- [1] McCutchen, C. W., 1959, "Sponge-Hydrostatic and Weeping Bearings," *Nature*, **184**, p. 1284.
- [2] McCutchen, C. W., 1962, "The Frictional Properties of Animal Joints," *Wear*, **5**, pp. 1–17.
- [3] Ateshian, G. A., Wang, H., and Lai, W. M., 1998, "The Role of Interstitial Fluid Pressurization and Surface Porosities on the Boundary Friction of Articular Cartilage," *J. Tribol.*, **120**, pp. 241–251.
- [4] Ateshian, G. A., Soltz, M. A., Mauck, R. L., Basalo, I. M., Hung, C. T., and Lai, W. M., 2003, "The Role of Osmotic Pressure and Tension-Compression Nonlinearity in the Frictional Response of Articular Cartilage," *Transp. Porous Media*, **50**, pp. 5–33.
- [5] Mow, V. C., Kuei, S. C., Lai, W. M., and Armstrong, C. G., 1980, "Biphasic Creep and Stress Relaxation of Articular Cartilage in Compression? Theory and Experiments," *J. Biomech. Eng.*, **102**, pp. 73–84.
- [6] Lai, W. M., Hou, J. S., and Mow, V. C., 1991, "A Triphasic Theory for the Swelling and Deformation Behaviors of Articular Cartilage," *J. Biomech. Eng.*, **113**, pp. 245–258.
- [7] Krishnan, R., Kopacz, M., and Ateshian, G. A., "Experimental Verification of the Role of Interstitial Fluid Pressurization in Cartilage Lubrication," *J Orthop Res*, In Press.
- [8] Park, S., Krishnan, R., Nicoll, S. B., and Ateshian, G. A., 2003, "Cartilage Interstitial Fluid Load Support in Unconfined Compression," *J. Biomech.*, **36**, pp. 1785–1796.
- [9] Lipshitz, H., Etheredge, 3rd, R., and Glimcher, M. J., 1976, "Changes in the Hexamine Content and Swelling Ratio of Articular Cartilage as Functions of Depth From the Surface," *J Bone Joint Surg Am*, **58**, pp. 1149–1153.
- [10] Torzilli, P. A., Askari, E., and Jenkins, J. T., 1990, "Water Content and Solute Diffusion Properties in Articular Cartilage," *Biomechanics of Diarthrodial Joints*, V. C. Mow et al., eds., Springer-Verlag, New York, pp. 363–390.

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