Response to Comment by Charles W. McCutchen

Gerard A. Ateshian

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.

Contributed by the Bioengineering Division for publication in the JOURNAL OF BIOMECHANICAL ENGINEERING. Manuscript received by the Bioengineering Division January 9, 2004; revision received January 16, 2004.

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