Technical Comments

Comment on "Bone Articulations as Systems of Poroelastic Bodies"

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NOWINSKI[1] calculates immediate and equilibrium deformations of loaded bone joints on the assumption that the bones behave as poroelastic bodies. I pass no judgement on the correctness of his mathematics, but question its relevance to cancellous (porous) bone. The bones are too small and too stiff, their pores are too big, and their marrow insufficiently viscous for them to behave as poroelastic bodies in Nowinski's sense.

A wad of steel wool is porous and elastic, but not poroelastic, because inertial reactions strongly influence its response to changes in loading. Poroelastic materials obey a diffusion equation. If the loading on a poroelastic body is suddenly changed the readjustment of the liquid distribution in the body diffuses into it from its pervious surfaces, reaching a depth l in a time t_1 given, for a semi-infinite body, approximately by

$$t_l = l^2/Mk \tag{1}$$

where M is the unidirectional compression modulus of the structure when lateral expansion is prevented, and k is its permeability[2].* The compressibility of the liquid is ignored; its effect is only about a tenth that of the compliance of the bone.

If the poroelastic material has thickness l, then by time t_l its stress and strain patterns will have completed most of the change from their initial to their equilibrium shapes.

For a human joint we take l as a generous 5 cm. The Young's modulus of cancellous bone is 10^9 dynes/cm^2 (Ref. 3). For an order of magnitude estimate we can take the Young's modulus as equalling M. The bone's structure is a very open sponge with pores about 1 mm in diameter. If we approximate it by a parallel array of 1-mm-diam tubes the permeability k is $(32\eta)^{-1}$ cm^4/(dyne sec), where η is the viscosity of the bone marrow.

Fat droplets make up most of the volume of the marrow. These lie within cells made largely of water. I have measured the viscosity of the fat at body temperature and find it to be about 1 poise, which should be an upper limit for the marrow viscosity.

Putting these values into Eq. (1) we find that the characteristic time t_l is about 10^{-6} sec. This interval is so short that with loads applied and removed at physiological rates the deformation will never differ significantly from the equilibrium pattern.

Only events like being struck by a bullet can apply load so quickly, and even here the poroelastic mathematics does not apply. Sound must travel slower in cancellous bone than the 3000–4000 m/sec that it travels in solid bone. In 10^{-6} sec the pressure wave from the impact will have travelled less than 4 mm, far less than the distance across the bone. This contradicts the assumption necessary to the poroelastic treatment, that inertial reactions can be ignored.

Though poroelastic effects are negligible in cancellous bone, the situation is otherwise in articular cartilage, the bearing material that covers the ends of the bones. Here $M = 6 \times 10^6$ dynes/cm^2 and $k = 5 \times 10^{-13}$ cm^4/(dyne sec) (Ref. 2). The surfaces of the underlying bones are impervious, so when two cartilages are squeezed together $2l$ is the width of their region of contact, 2 cm or so in man and domestic animals. This makes $t = 80$ hr, which is reduced to nearer 1 hr by an abrupt increase in M that starts as the compressive strain passes 0.5, and by the smaller numerical constant that is obtained in this somewhat different situation.[2]

During this hour pore fluid from the cartilages provides self-pressurized hydrostatic, or weeping lubrication for their rubbing surfaces. When the load is removed and the cartilages separated each resoaks a new charge of liquid through its surface and thus prepares itself for the next period of load carrying.

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* The relevant section of Ref. 2, pp. 10–11, contains an error. The quantity a should be removed from all equations on these pages.

References

[1] Nowinski, J. L., "Bone Articulations as Systems of Poroelastic Bodies in Contact," *AIAA Journal*, Vol. 9, No. 1, Jan. 1971, pp. 62–67.

[2] McCutchen, C. W., "The Frictional Properties of Animal Joints," *Wear*, Vol. 5, No. 1, 1962, pp. 1–17.

[3] Yamada, Y. and Evans, F. G., *Strength of Biological Materials*, Williams and Wilkins, Baltimore, 1970, p. 74.