Weeping Lubrication

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Given the opportunity to speak for fifteen minutes at the 7th World Congress of Biomechanics, July 6-11, 2014 in Boston Mass, I elected to talk about weeping lubrication, a consequence of the fluid in the pores of articular cartilage. Most current research on joint lubrication studies the lubricating ability of synovial fluid, lubrication needed because high spots on opposing cartilages push against each other. This stress is given by the joint's unit loading **minus the pressure in the cartilage pores -- and the pressure depends on the history of the joint loading.**

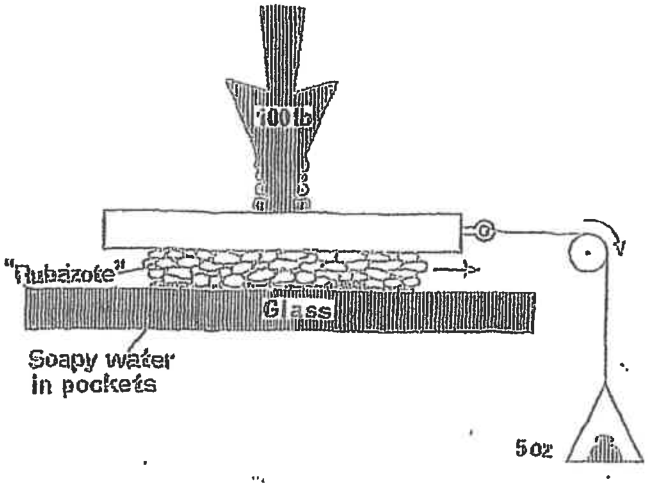
To be sure that the contacting high spots carry almost all the joint load in an experiment, the cartilage sample or samples must be very thin and on backing with negligible flow resistance, say sintered glass. See the caption of Fig. 11 in McCutchen, C. W., 1962a. When load is applied the pore pressure will quickly fall to near zero. I also used, but did not describe, this arrangement in the experiment reported by Fig. 1.4 of McCutchen, C. W., 1967.

I have no recollection that others have used this method.

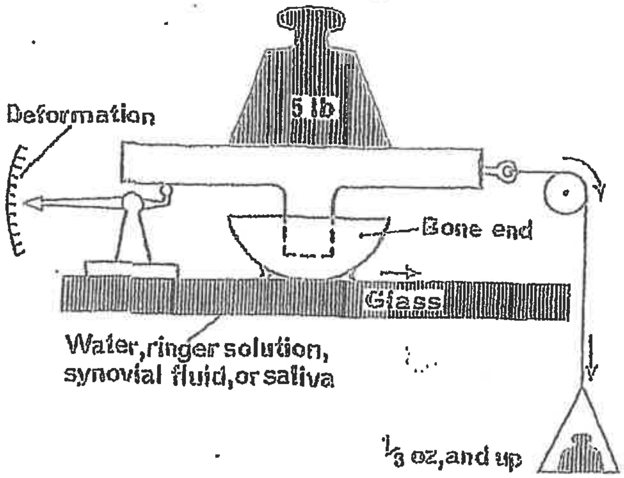
As the conference's little lectures were not published, I expanded the text and submitted it to *Biotribology*, which rejected it. Further expanded by footnote 2 on page 5, here it is.

In the talk all the figures were on a single slide illuminated for the duration. Similarly, here they are.

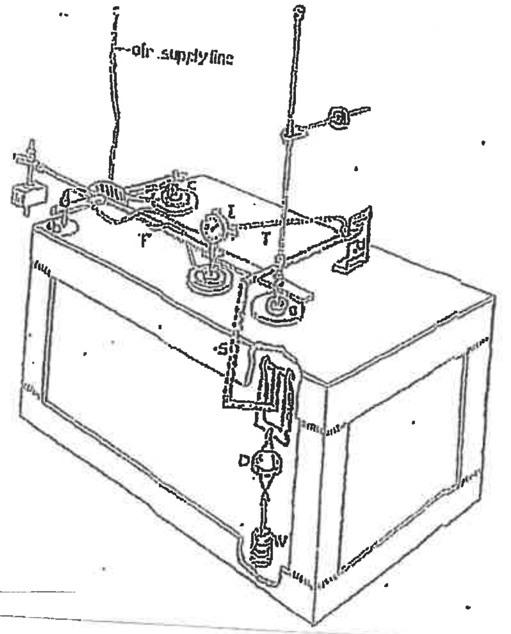
1


100 lb
"Rubazote"
Glass
Soapy water in pockets
5 oz

2


Deformation
5 lb
Bone end
Glass
Water, ringer solution, synovial fluid, or saliva
1/3 oz, and up

3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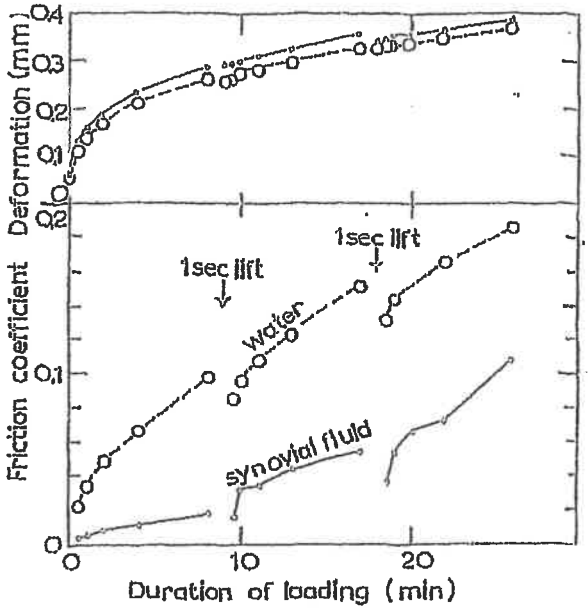
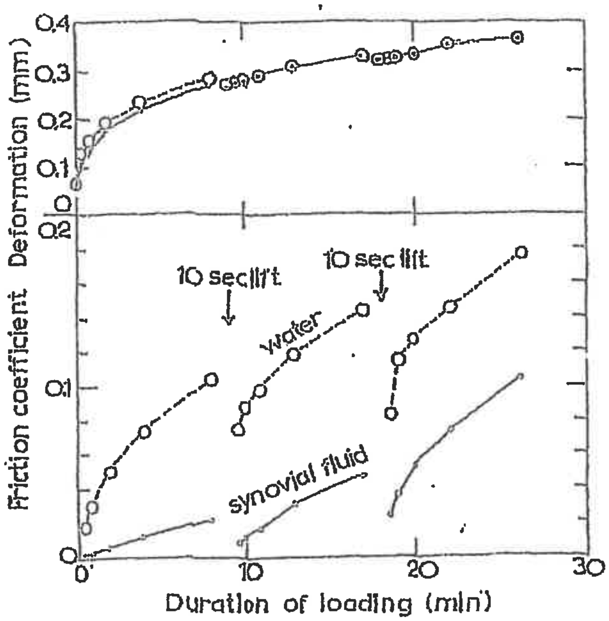
4


Deformation (mm)
0.4
0.3
0.2
0.1
0
Friction coefficient
0.2
0.1
0
1 sec lift
1 sec lift
water
synovial fluid
0
10
20
Duration of loading (min)

5


Deformation (mm)
0.4
0.3
0.2
0.1
0
Friction coefficient
0.2
0.1
0
10 sec lift
10 sec lift
water
synovial fluid
0
10
20
30
Duration of loading (min)

6

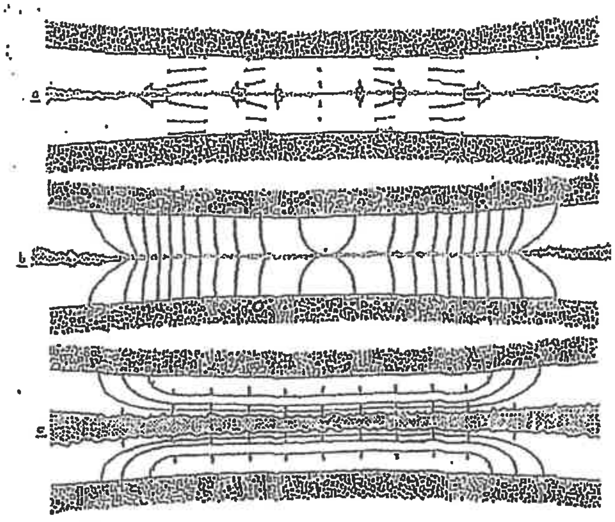

a
b
c

Figure Captions:

1) A "Rubazote" pad carrying load (magnified)

2) The friction and deformation rig in principle

3) The friction and deformation rig in fact

4) Friction and deformation with the passage of time with one second lifts

5) Friction and deformation with the passage of time with ten second lifts

6) From an electronic analog:
6a and 6b show fluid flow direction and illustrate the isobars respectively when carrying load.
6c illustrates the isobars when resoaking.

Abstract

Joint cartilage has been slippery since dates were named for places (*e. g.*, "Devonian" for Devon, "Cretaceous" for Crete) but the physical cause, hydrostatic lubrication by pressurized pore fluid, was discovered only in 1959. Experiments and theory were good fun, and uncovered two surprises.

1. Cambridge, UK, 1959

I read an article in the *New Scientist* by orthopedic surgeon John Charnley. Because the swinging of a pendulum with an excised animal joint as pivot decayed linearly with time, Charnley thought the joint cartilage provided boundary lubrication. It was super-Teflon.

I doubted this, having earlier imagined the principle of self-pressurized hydrostatic lubrication provided by fluid-filled, endwise-compressible cylinders, each with an open end facing a smooth rubbing surface. In the research room next to mine in the Cavendish Laboratory D. A. G. (Tony) Broad made a glovebox sealed with a gasget, perhaps a quarter inch thick, of "Rubazote," a sponge with closed cells .7 millimeter and less in diameter;

congealed rubber wihipped cream. Cut it, and the cut surface consists of noncommunicating pockets. Lubricated with soapy water, the friction coefficient of the pocketed face against glass was about 70% that of its smooth, uncut face, not a dramatic difference.

Fortnately the bathtub where I lived was a floor above its touchy, gas fired "Ascot" water heater,[1] so I would sneak showers in the Gonville and Caius College megabath.[2] Post shower, playing with a soapy, 2 cm square, pocketed "Rubazote" sample in one of the sinks, I noticed that pushing it harder against the sink's surface had little effect on its friction. Soon I was using a letter scale to tow a hundred-pound weight across a big glass plate as it sat on little, soapy Rubazote pads. See Figure 1 (McCutchen, 1959). Nature, and *Nature* approved of self-pressurized, hydrostatic lubrication.

The surfce of cartilage is not pocketed.[3] But it is porous, compressible and fluid-soaked. Peter Lewis and I, mostly Peter, showed that squeezing it made it weep fluid which, like that in the cut cells of Rubazote, could carry load. Further, by measurig the sodium/potassium ratio of the wept fluid Peter showed that it was extracellular; it was fluid that the cartilage could lose and

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[1] To run the Ascot: 1) Fully open the tub's hot tap. The Ascot's main burner lights, and warm water flows. 2) Slowly close the hot tap. The water gets warmer. Close it too much; the Ascot throttles back to pilot light and the water runs cold.

[2] Where all the fixtures but the toilet drained into a shallow trench in the concrete floor.

[3] If it were, pressurized fluid would escape by zig-zagging from pockets on one surface to pockets on the other.

regain without damage to its cells (Lewis and McCutchen, 1959; 1960).

Perhaps prodded by F. P. Bowden, G. Salomon, editor of *Wear*, asked if he could republish the *Nature* material. There resulted a four-month contract from Bowden's group, paid for by a little British plastics company for research on the friction of polymers.[4] An expanded article emerged (McCutchen, 1962b),[5] covering the stiffness and permeability of cartilage, the fact that its friction against glass started very low and rose with time as the pore fluid oozed away (as it had with the Rubazote bearing); also the fact that human synovial fluid[6] lubricated much better than water or physiological saline -- but, a surprise, its advantage shrank as it got too heavily loaded.[7]

Figure 2 is the friction and deformation rig in principle, Figure 3 shows it in fact. Figures 4 and 5 give the results, deformation at the top, friction below. The friction with synovial fluid starts to catch up to that with water as time passes.

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[4] I may never have been told the company's name.

[5] Much of my four-month contract (December through March, by myself with a one or two kilowatt radiant heater in an otherwise unheated, defunct aircraft factory, Colloid Science's "Short Site,") was spent fumbling at why synovial fluid lubricates better than water or saline. Did the lubricant carry load via the osmotic pressure of long, less than close-packed chains of adsorbed polymer molecules? (I used thermodynamics on this in McCutchen, 1966.) Later Jim Wilkins and I measured the effect of various salts at various concentrations on the lubricating ability of synovial fluid from which the small protein molecules had been removed (McCutchen and Wilkins, 1969).

[6] provided by J. E. Stanier via the good offices of Anita I. Bailey

[7] *i. e.*, above 1.5-4.5 atm (McCutchen, 1967); above 4 atm (Zappone *et al.*, 2007)

In the "lifts" the rubbing surfaces were separated for one and later ten seconds to reform a "squeeze film." Friction rose much faster than it had when load was first applied. A squeeze film could not be the cause of its initial slow rise.

2. How does an ordinary bearing work at low rubbing speed?

When impervious surfaces are pushed together the squeeze-film of fluid between them at first carries all the bearing load, but soon the film is thin enough that high spots on opposing surfaces touch each other. Via the channels surrounding the high spots the fluid continues to squirt from between the surfaces, allowing the high spots to compress and carry more and more of the load until eventually they carry it all. Friction rises throughout this interval of "mixed lubrication."

3. Now add weeping

Loading cartilage raises the pressure in its pores almost to the value of the joint loading. Suppose the channels surrounding the contacting high spots are 600Å thick -- compared to the 60Å diameter of the cartilage pores. Escaping fluid will flow about a hundred times faster in the channels than in the pores, so the pressure in the film liquid soon drops to below that in the cartilage. Fluid will flow from the cartilages into the film (McCutchen, 1973).

Figure 6 part a, from an electrical analog, gives the flow pattern and part b illustates its isobars (McCutchen, 1975). Think of cars leaving local roads to use a superhighway. This wept fluid largely replaces that escaping along the channels and enormously lengthens the period of mixed lubrication. Friction rises much more slowly.

4. Wait, wait: Gerard Ateshian doubts weeping flow

That is because his mathematics (Ateshian, Lai, Zhu and Mow, 1995) assumes zero space between the rubbing surfaces and thus no passage for the escape of wept fluid. He told me the roughnesses of cartilage would squash each other flat under the joint load. (We will see later that he nevertheless does not think they touch each other everywhere.)

5. In operation

A weeping bearing must resoak fluid through its rubbing surfaces between intervals of load carrying. Figure 6, part c, illustrates isobars of the flow pattern. Thanks to the poor fit of joint surfaces one to another this will happen from time to time and place to place as the joint flexes (McCutchen, 1962b).

The periods of load carrying on any one spot must be short enough that the load not carried by hydrostatic pressure is too small to defeat synovial fluid's ability to lubricate.

Fluid flows in cartilage obey consolidation theory. Not knowing that such existed, I derived one in 1962 (McCutchen, 1962b), making a nonfatal error corrected by 1974 (McCutchen, 1974 and 1975).

6. Enter hydrostatic clamping, a gripping idea

Where high spots on opposing surfaces come into contact they are forced together by the hydrostatic pressure in the fluid as well as by the elastic stress in the cartilage skeletons. I expected this hydrostatic clamping to cause friction, to minimize which the rubbing surfaces should have the smallest possible area of real contact (McCutchen, 1962b).

7. But does hydrostatic pressure raise friction?

The assumed but as far as I knew undemonstrated effect of hydrostatic pressure on friction nagged at me, but I saw no easy way to measure it. Then I asked M. King Hubbert, and he told me how.[8] Surprise #2: I found no effect on

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[8] The Hubbert method: Held in a lathe chuck is a transparent, blind-ended plastic tube full of water. It contains an air-filled, conical, closed-arm manometer for measuring pressure, and a cylindrical, open-ended glass ampoule containing friction samples. Plugging the open end of the plastic tube is an O-ringed piston that applies pressure when pushed by the lathe's tailstock. Surrounding the plastic tube is a larger, transparent plastic tube to stop flying pieces if the apparatus bursts. Rotate the lathe chuck at increasing pressures and see how far the samples follow the ampoule's wall upward before slipping.

cartillage friction up to 100 atm. Then the apparatus blew up (McCutchen, 1978).[9]

Theory approves. Because hydrostatic pressure pushes in all directions, it does not increase the area of the real contacts, so the adhesion theory (Bowden and Tabor, 1950; Moore, 1972) predicts no change in friction (McCutchen, 1978).

Evolution heaved a sigh of relief. The area of real contact did not have to be small; the lubricant in synovial fluid did not have to survive the high concentration of solid stress that would otherwise have resulted. (Yet to be tested is whether the lubricating effect of synovial fluid is likewise little effected by hydrostatic pressue.)

8. How big is the area of real contact? I do not know.

Ateshian loaded a cartilage *vs.* glass bearing, and measured friction and pore pressure as time passed. From these data he calculated the friction contributed by pore pressure (he believed in hydrostatic clamping). It was very small. That told *him* that the fractional area was very small (Ateshian, 2009). It tells *me* that as hydrostatic pressure has little effect on friction, friction cannot be used to measure the area of real contact (McCutchen,

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[9] Keith Martin at the library of the National Institute of Science and Technology later found that Brisco *et al.* (1974) had four years earlier found that the friction of several polymers *dropped* a few percent at 100 atm, with no great change even at 1,000 atm.

2009b).

9. Arthritis

Weeping lubrication has been fun to experiment with and think about, but the cause or causes of arthritis are probably chemical; likewise any cures. The field needed chemists, and in David Swann it got one. In 1970 Radin, Swann and Weisser found that the prime lubricant in synovial fluid was the previously unknown glycoprotein, lubricin.

By 1986 NIH had defunded Swann's group.

10. Stresses, a tale of two systems

There are two obvious ways to bookkeep pore pressure. Stress-separation takes pore pressure as existing only in the fluid, so one needs to know how much of a material's volume the fluid occupies. This tempted people[10] into giving this value a false, mechanical significance.

In stress-superposition the pore pressure permeates the entire volume, so the fluid fraction does not enter the mathematics. The gross stress felt by the confining walls minus the pore pressure is the biomechnician's "solid stress;" the "deviatoric stress" of geologists.

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[10] (in particular at Rensselaer Polytechnic Institute)

At different times M. A. Biot used both systems. His 3-D treatment uses stress-separation, but he noted that it could be done with stress-superposition (Biot and Willis, 1957). I did so in 1998.

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