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Lubrication and cartilage*

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INTRODUCTION

There are two main types of lubrication – that in which articulating surfaces are separated by a fluid film, and that in which the load is supported by surface-to-surface contact, molecular protection being afforded by layers attached to the surface (boundary lubrication): these layers usually come from an 'additive' in the lubricating fluid (Fig. 1). Fluid film lubrication may be achieved by a hydrodynamic or entraining action in which surface motion draws in a film of fluid between the solids. When the bearing material (as in cartilage) is soft it may deform under the hydrodynamic pressures and elastohydrodynamic lubrication will occur. When two surfaces approach each other in the normal direction a film of fluid may be trapped between them, thus giving rise to squeeze film lubrication. When the fluid is pressurized externally another form of fluid film lubrication known as hydrostatic lubrication prevails.

In considering a problem of lubrication three factors must be considered:

(1) The operating conditions (e.g. loads and speeds).
(2) The lubricant (e. g. synovial fluid).
(3) The bearing surfaces (e.g. articular cartilage).

Loads

It has been well demonstrated that the load on the hip joint in a walking cycle may go up to three or four times body weight at heel-strike and toe-off (Paul, 1967). On the knee, similar work carried out by Morrison (1968) has shown that the peak load during a walking cycle may rise to three times body weight. Smith (1972) has shown that, in a vertical drop of one metre, the load on the knee may go up to 25 times body weight (Fig. 2).

Cartilage

From the point of view of lubrication it is important to remember that cartilage is a deformable solid. Its elastic modulus with zero creep is about 20 MN/m^2 (Johnson, 1974). This is similar to the elasticity of synthetic rubber as used in a car tyre (Table 1).

Cartilage is also porous, which is important in its nutrition, and has a bearing on its deformation under load, in that much of the deformation is due to the movement

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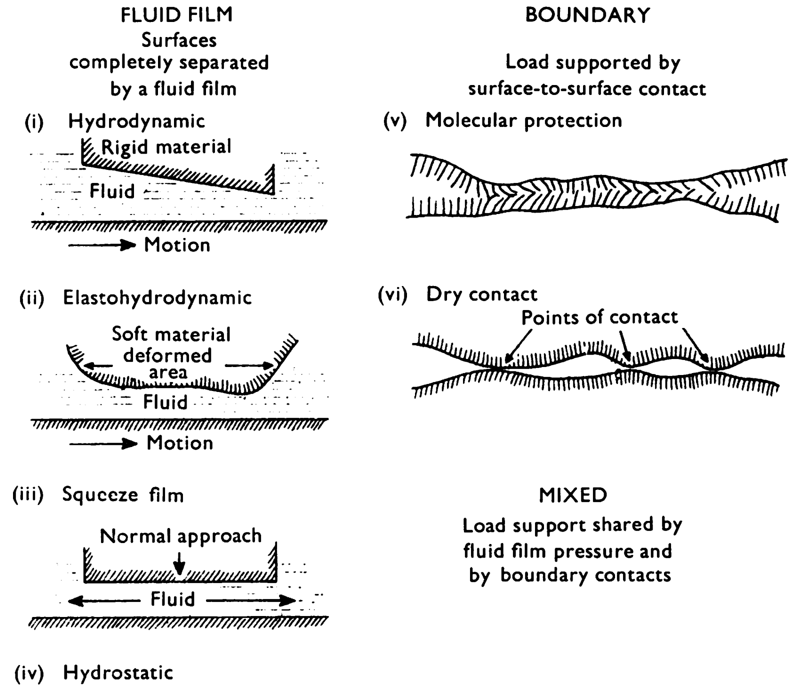

Fig. 1. Types of lubrication between two surfaces, loaded together.

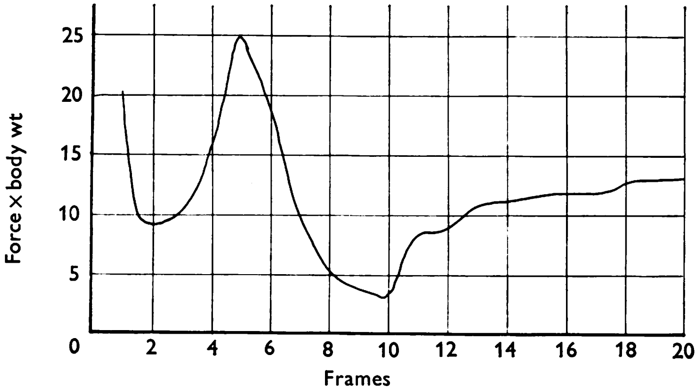

Fig. 2. Compressive force at knee landing from 1 m.

of fluid from the matrix. It also enables the cartilage to exude fluid. This is the basis of the 'weeping lubrication' model proposed by McCutchen (1959), in which he suggested that, under load, fluid is exuded from the cartilage between the loaded surfaces, producing a self-generating hydrostatic bearing.

The cartilage surface was thought to be smooth at one time (Ghadially & Roy, 1969), but measurements of the surface quality of acrylic castings by a talysurf have shown that, in engineering terms, the surfaces are remarkably rough (Fig. 3). The

Table 1. *Elastic modulus of some materials (mn/m²)*

Synthetic rubber	3·5–70
Vulcanized rubber	3500
PVC	350
Nylon	2800
Cartilage	12–50

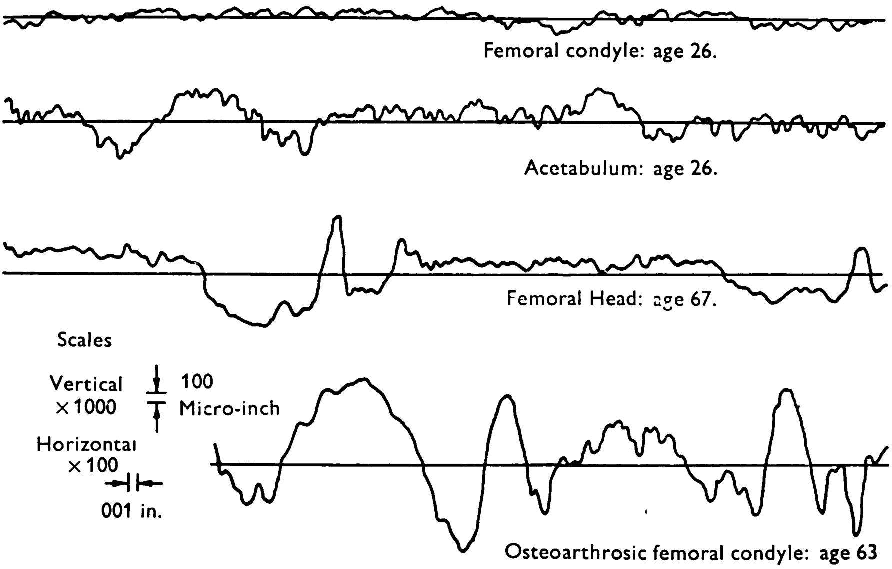

Fig. 3. Typical talysurf traces taken from acrylic castings of cartilage.

centre line average of fetal cartilage is 1 μm, that of 67 year old cartilage 2·75 μm, and of osteoarthrosic cartilage 5·25 μm. This has been directly visualized with scanning electron microscopy (Walker *et al.* 1968; Gardner & Woodward, 1969). This unevenness of the cartilage may result in pools of fluid being trapped, when the joint is loaded, and is one aspect of the 'boosted lubrication' model proposed by Dowson *et al.* (1968), in which it is suggested that synovial fluid is trapped, and concentrated by the leakage of a watery component sideways between the cartilage surfaces and possibly to a lesser extent into the cartilage, leaving a greater concentration of mucin in the pools. This is in keeping with the observations of Maroudas (1967), who showed the formation of gels on the surface when synovial fluid was filtered through the cartilage.

That cartilage is important in the lubrication of joints is shown by experiments in which a reciprocating friction machine (Walker, Dowson, Longfield & Wright, 1968) was used to measure the friction force with various types of cartilage. Conversely, experiments in which normal cartilage was used with a variety of synovial fluids have shown that the synovial fluid is also important in this situation.

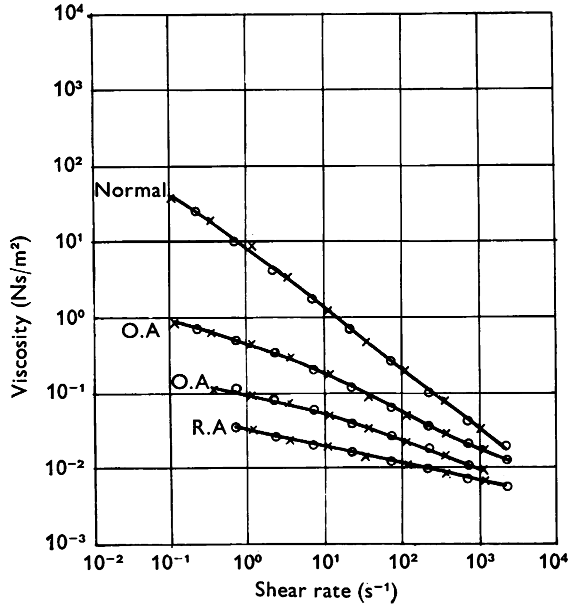

Fig. 4. Viscosity–shear rate relationships of normal and arthritic synovial fluid.

Synovial fluid

Synovial fluid is non-Newtonian in that its viscosity decreases with increased shear rate (Davies & Palfrey, 1969; Vos & Theyse, 1969). The viscosity–shear rate relationships of normal and disease synovial fluid are shown in Figure 4.

EXPERIMENTAL OBSERVATIONS

To examine the lubrication regimes in more detail we have used a pendulum machine which incorporates the facility to apply sudden loads to the joint on starting the swinging motion, and also the ability to measure directly the frictional torque experienced by the joint (Unsworth, Dowson & Wright, 1974). Others have used pendulum machines (Jones, 1934; Charnley, 1960; Barnett & Cobbold, 1962; Little, Freeman & Swanson, 1969) and have concluded (with the exception of Jones) that the mode of lubrication was boundary in nature. These conclusions were based on an apparently linear decay in the amplitude–time curve. The relationships between friction and time that would be expected with various types of lubrication in a pendulum apparatus are shown in Figure 5*A*, *B* and *C*. Results from a series of experiments in which a natural hip joint was lubricated with synovial fluid and a load was either suddenly or continuously applied, were compared with those from a joint wiped dry (Figs. 6–9). It will be seen that with a suddenly applied load in a joint lubricated with synovial fluid the relation was that which one would expect from a squeeze film situation. Where the joint was continuously loaded the curve was similar to that which one would anticipate with elastohydrodynamic lubrication. The

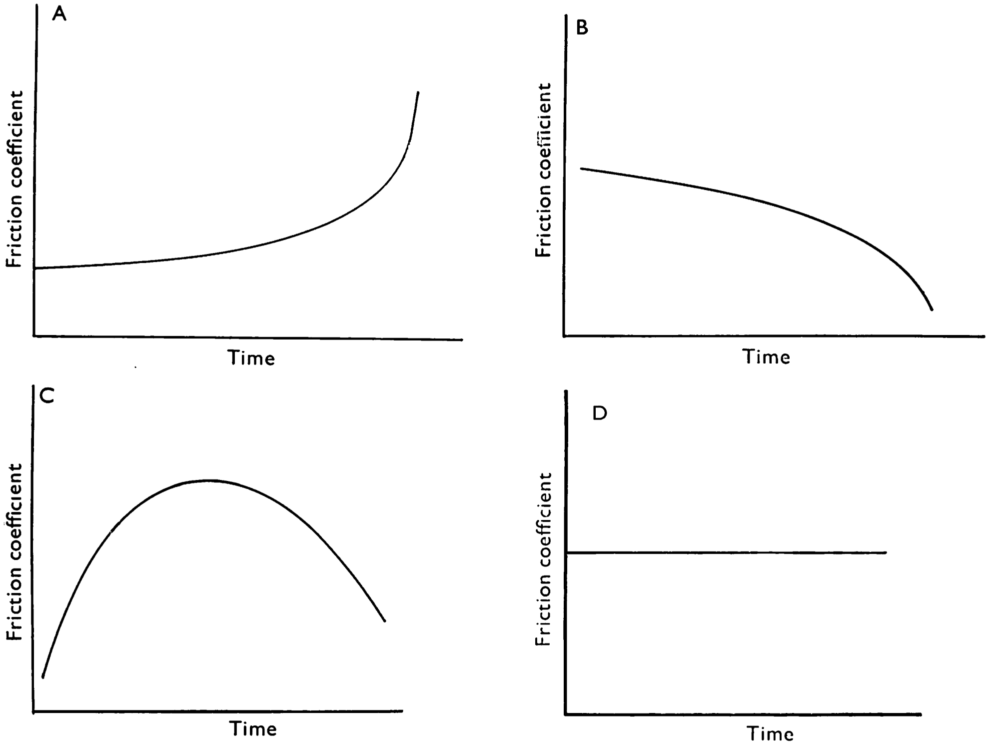

Fig. 5. (A) Relation of coefficient of friction with time during hydrodynamic lubrication; (B) relation of coefficient of friction with time during elastohydrodynamic lubrication; (C) relation of coefficient of friction with time during squeeze film lubrication; (D) relation of coefficient of friction with time during boundary lubrication.

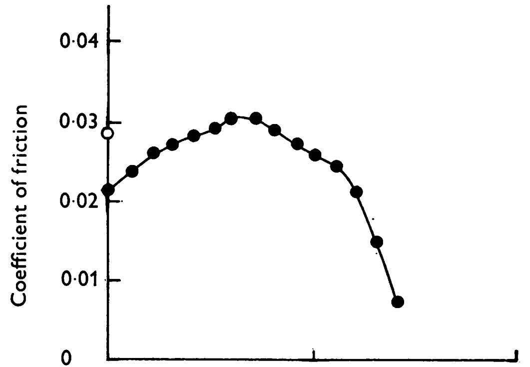

Fig. 6. Hip joint lubricated with synovial fluid – suddenly applied loads (213 N).

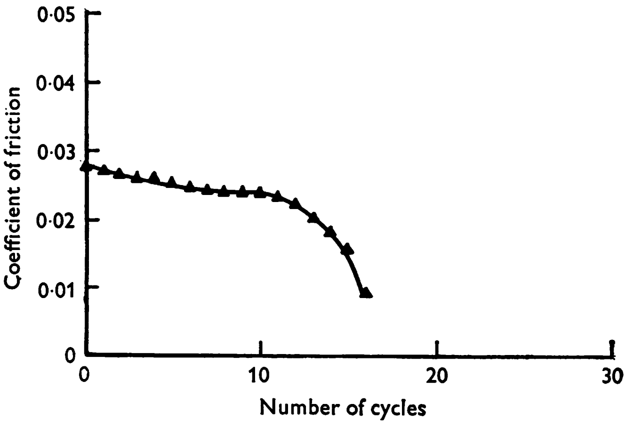

Fig. 7. Hip joint lubricated with synovial fluid – static (continuously) loaded (800 N).

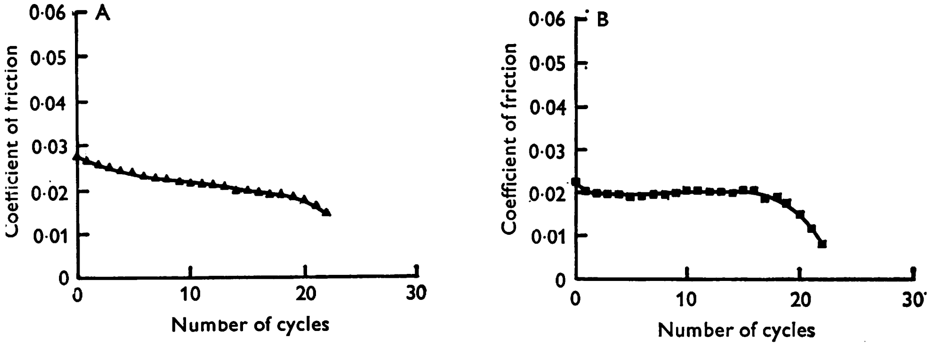

Fig. 8. A, B, Hip joint dry – suddenly applied loads (577 N).

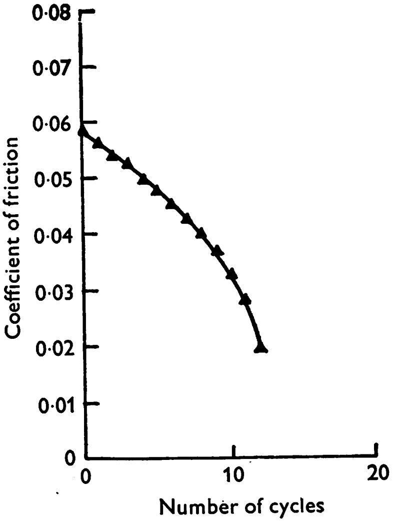

Fig. 9. Hip joint dry – static (continuously) applied loads (800 N).

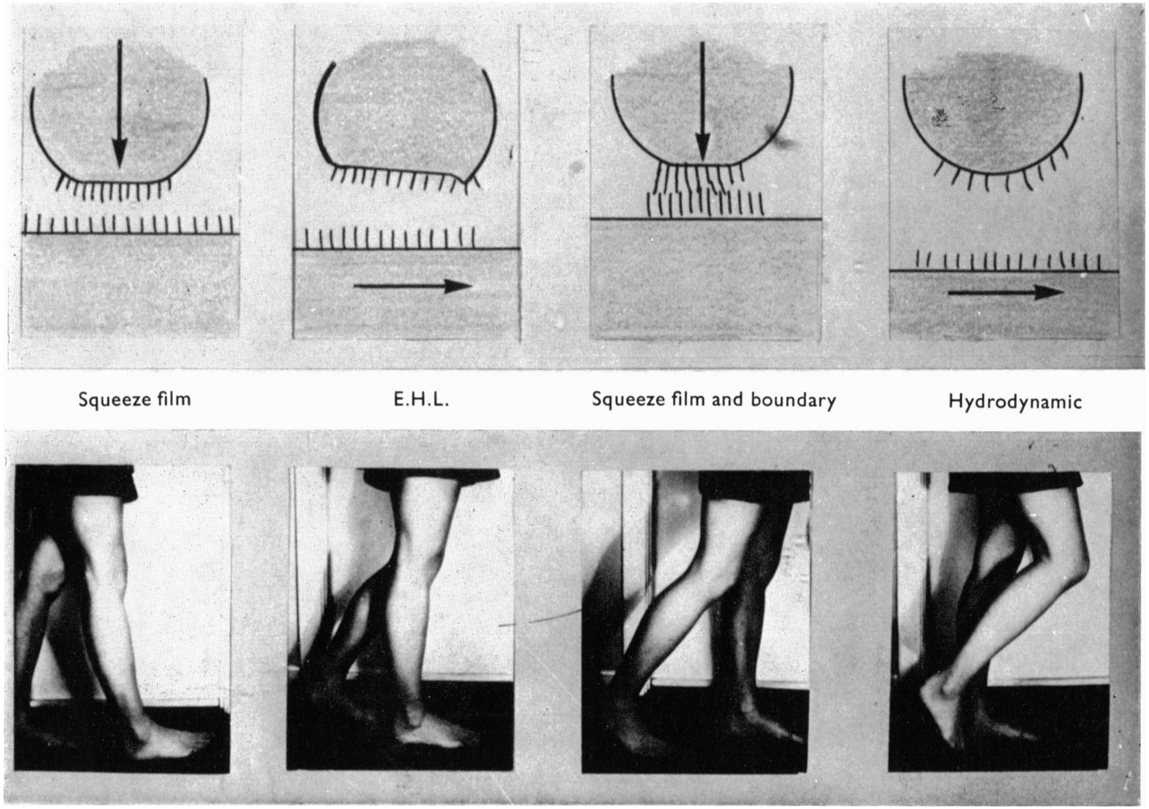

Fig. 10. Lubrication regimes at different stages of a walking cycle.

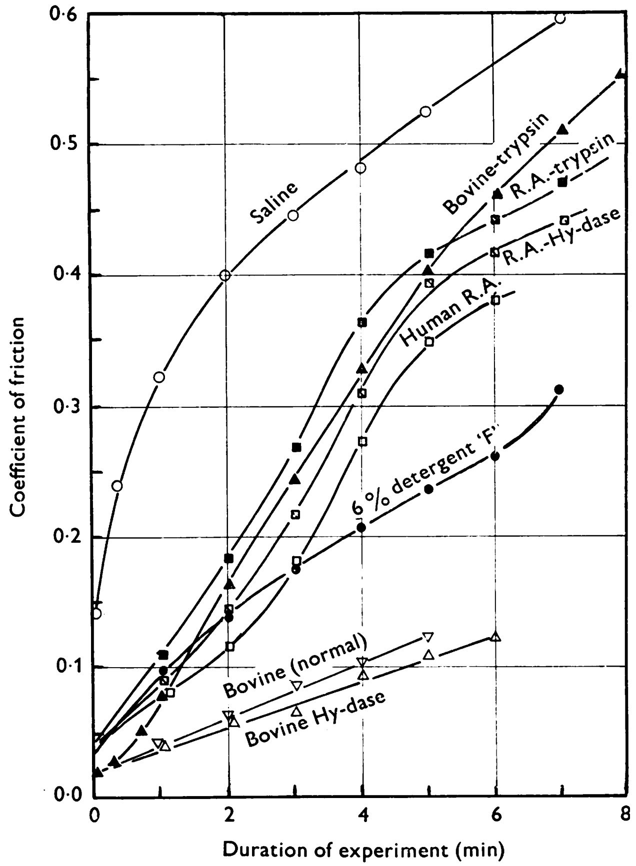

Fig. 11. Coefficient of friction of saline, bovine and rheumatoid synovial fluid before and after digestion with hyaluronidase and trypsin.

behaviour of the dried natural joint with suddenly applied loads was that of a boundary lubrication situation, while reduction of friction in the joint when the load was continuously applied suggests that fluid was squeezed out of the cartilage, thus enabling an elastohydrodynamic lubrication regime to develop.

CONCLUSIONS

There is evidence to believe, therefore, that a variety of types of lubrication operate in human synovial joints (Fig. 10). At heel-strike a squeeze film situation may develop, leading to elastohydrodynamic lubrication and possibly both squeeze film and boundary lubrication, while hydrodynamic lubrication may operate during the free swing phase of walking.

The work of Radin, Swann & Weisser (1970) in which synovial fluid was digested with hyaluronidase and trypsin suggests that hyaluronate is not important in the type of lubrication they were investigating. Using the reciprocating friction machine

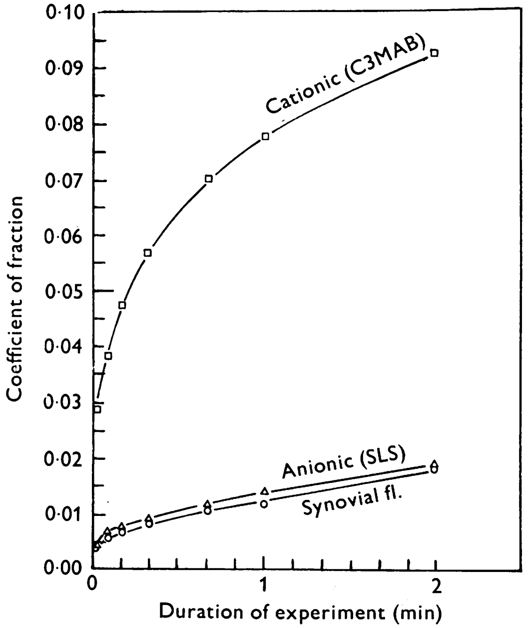

Fig. 12. Coefficient of friction using synovial fluid, sodium lauryl sulphate (SLS) and cetyl-3-methyl ammonium bromide (C3MAB).

in which boundary lubrication prevailed, we have shown similar results (Gvozdanovic, Wright & Dowson, 1974). When the hyaluronate molecule was destroyed the viscosity of synovial fluid became virtually that of water. Nevertheless the lubricating properties of the fluid remained the same (Fig. 11). Destruction or isolation of the protein factor of the fluid did not affect its viscosity but reduced its lubricating ability considerably. It is interesting in our experiments to note that the proteolytic enzyme-degraded fluid failed under load much quicker than untreated fluid. Since the viscosity is unchanged this cannot be explained by squeeze film action but only in terms of some lubricating layer on the cartilage.

It might be anticipated that other substances would form such layers also. We have endeavoured to lubricate cartilage with solutions of two surface active substances (the anionic substance, sodium lauryl sulphate, and the cationic substance, cetyl-3-methyl ammonium bromide). The viscosity of the solutions was practically that of water, but the lubricating ability was similar to synovial fluid (Fig. 12). The anionic substance was better than the cationic one, although both were far superior to saline. The anionic substance was more effective in an alkaline medium and the cationic one in an acidic medium (Fig. 13). The variations of pH did not affect the viscosity of the solution, but only their dissociation and ability to form surface monolayers.

A schematic representation of the cartilage–glass interface is shown in Figure 14. Some asperities of cartilage may break through the lubricating layer, but some residue of the lubricant remains also. The load and duration of continuous loading

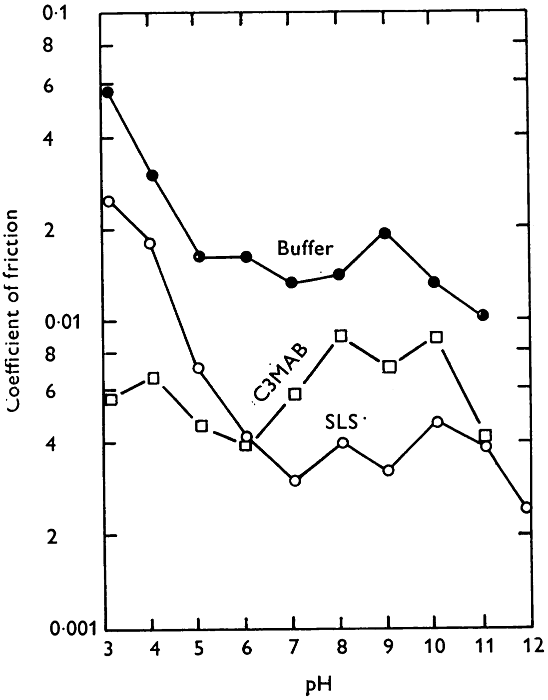

Fig. 13. Variation of coefficient of friction with pH using a cationic and anionic lubricant. Cartilage on glass. Pressure: 3·5 MPa. Load: 25 N. Speed (max.): 12 mm/s.

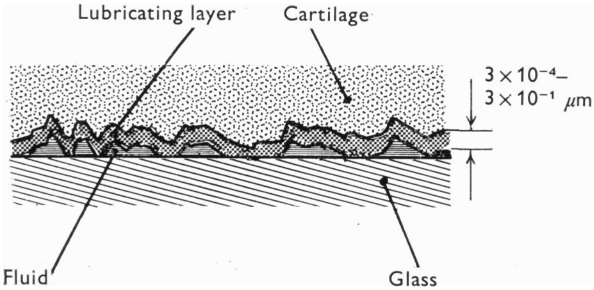

Fig. 14. Schematic representation of cartilage–glass interface.

will obviously affect this situation *in vivo*, the lubricating layer being slowly destroyed by continuous loading.

SUMMARY

Mechanisms of lubrication of human synovial joints have been analysed in terms of the operating conditions of the joint, the synovial fluid and articular cartilage.

In the hip and knee during a walking cycle the load may rise up to four times body weight.

In the knee on dropping one metre the load may go up to 25 times body weight.

The elastic modulus of cartilage is similar to that of the synthetic rubber of a car tyre.

The cartilage surface is rough and in elderly specimens the centre line average is 2·75 μm.

The friction force generated in reciprocating tests shows that both cartilage and synovial fluid are important in lubrication.

The viscosity–shear rate relationships of normal synovial fluid show that it is non-Newtonian. Osteoarthrosic fluid is less so and rheumatoid fluid is more nearly Newtonian.

Experiments with hip joints in a pendulum machine show that fluid film lubrication obtains at some phases of joint action.

Boundary lubrication prevails under certain conditions and has been examined with a reciprocating friction machine.

Digestion of hyaluronate does not alter the boundary lubrication, but trypsin digestion does.

Surface active substances (lauryl sulphate and cetyl 3-ammonium bromide) give a lubricating ability similar to that of synovial fluid.

The effectiveness of the two substances varies with pH.

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