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DEMONSTRATION OF BOUNDARY LUBRICATION BY SYNOVIAL FLUID

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Human and animal joints have a much lower friction than man-made bearings. This is due partly to the synovial fluid which acts as a lubricant and partly to the soft microporous nature of the articular cartilage. The mechanism whereby the lubrication is provided is still a matter of discussion. Different theories have been advanced. Hydrodynamic lubrication (MacConaill 1932) gives low friction as the sliding surfaces soak a film of viscous fluid into the load-bearing area and are forced apart by this fluid. This form of lubrication is most feasible when motion takes place in one direction only.

In 1959 Charnley introduced the theory of boundary lubrication. He demonstrated that in human joints the cartilage surfaces slide freely over each other with low friction without synovial fluid; this is due to boundary lubrication provided by adsorption of a layer of the macromolecules of the synovial fluid on the cartilage surface. Boundary lubrication depends only to a small degree on viscosity and speed; it is more dependent on the physico-chemical properties of the bearing surfaces.

In 1966 McCutchen put forward the theory of weeping lubrication based on the old theory that cartilage when compressed presses fluid out onto the bearing surface. Furthermore Dintenfuss (1967) has mentioned the prospect of an elastohydrodynamic lubrication mechanism.

The aim of this report is to present an apparatus able to demonstrate boundary lubrication by synovial fluid and to expound different factors which may influence the results achieved.

The apparatus is constructed by the Medicotechnical Institute, Academy for the Technical Sciences, Copenhagen, in accordance with an

American construction devised by C. W. McCutchen, National Institutes of Health, Bethesda, Maryland.

EXPERIMENTAL DESIGN

Technical description

The principle on which the measuring method employed in this study is based is also used industrially. The fluid to be studied is placed between two carefully specified plates of which one is set in rotation. By means of the friction between the plates and the fluid this rotation will be transmitted to the other plate, which is spring-loaded. Using a displacement transducer the rotation angle of plate number two is measured.

The measuring apparatus

The primary section of the apparatus (Figure 1) is the measuring unit which is placed in the middle of a frame made of aluminium. The measuring unit consists of a shaft held in a vertical position by means of two precision bearings. The bottom the shaft is connected to a motion cylinder by means of a coupling which can transmit rotary oscillations only. The top the shaft is provided with a weight. This weight together with the weight of the shaft and the weight of the motion cylinder with the desired load (150 g) presses the motion cylinder against the base plate. A rubber cover of 7/100 mm thickness is drawn around the lower end of the motion cylinder. The rubber cover is fastened by means of a rubber ring.

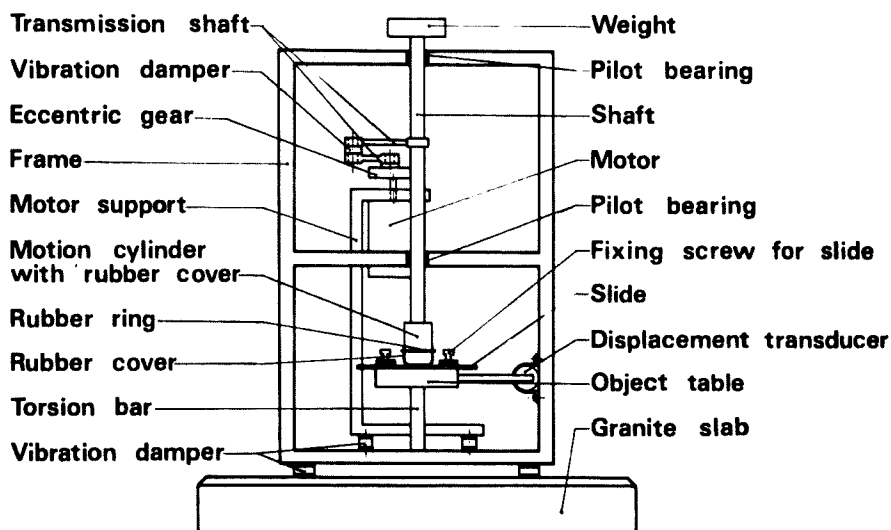


Figure 1. Diagram of the apparatus for friction measurement and demonstration of boundary lubrication by synovial fluid. The diagram shows the mechanical unit placed on the granite slab. Full size 20 × 30 × 10 cm.

Below the motion cylinder a slide is placed on an object table. The fluid to be studied is placed on the slide between it and the rubber-covered end of the motion cylinder. It is the intention to keep the two surfaces, the slide and the rubber-covered end of the motion cylinder, parallel during the entire measuring process. Moreover, in the rubber-covered end of the motion cylinder a hollow has been turned with the purpose of making the rubber contact point with the slide a circle with an inside diameter of 13.0 mm and an outside diameter of 15.4 mm.

The holder of the slide is fastened to the bottom plate of the frame by means of a torsion bar, which at the same time acts as a spring with a calculated force. The torsion bar thus allows the lowest part of the measuring system (slide and holder) to rotate through a few degrees without friction and wobble.

The registration of the rotation of the lowest part of the measuring system is done by means of a displacement transducer of which one section is fastened to the frame while the other section is connected to the holder of the slide by a shaft. The electric signal from the displacement transducer is fed via an electronic unit to an ink recorder (Hukushin R 130-0-A). The rotational oscillation which goes first one way and then the other with a total angular sweep of 33°, comes from a non-vibrating motor. The motor is, moreover, fixed to an angle bar connected with the frame by means of four vibration dampers only. The speed of the motor is controlled and kept constant by the electronic unit.

The transformation of the rotational oscillation of the motor shaft to the reciprocating motion of the shaft is effected by an eccentric gear fixed to the motor shaft. The transmission of the motion to the shaft is carried out by means of an operating lever device constructed to transmit the reciprocating oscillation without wobble.

The aluminium frame is the bearing element of the set-up and keeps the primary components in the correct positions in relation to each other. It is placed on four vibration dampers on a granite slab measuring 50 × 50 × 8 cm in order to avoid the transmission of vibrations from the surroundings to the aluminium frame, and in this way to the measuring system.

Calculation

The friction is stated in terms of the coefficient of friction (μ).

Calibration of the measuring equipment is performed by placing a shaft of fixed length in a hole made for that purpose in such a way that the shaft points radially away from the slide holder. A string is fastened to the end of the shaft and drawn over pulleys positioned one on each side of the aluminium frame. At the end of the string a weight (3.3 g) is placed.

The calculation is made on the basis of the curves traced on the ink recorder (Figure 2); the amplitude is measured in square units, peak-to-peak, and is multiplied by a factor K representing the constant of the apparatus. K is worked out according to the formula:

$$K = \frac{b \text{ g/cm}}{r \text{ cm} \cdot M \text{ g} \cdot X_1}$$

in which b is the weight of the calibration plumb multiplied by the length of the lever arm (24.7), r is the mean radius of the point of contact of the rubber cover

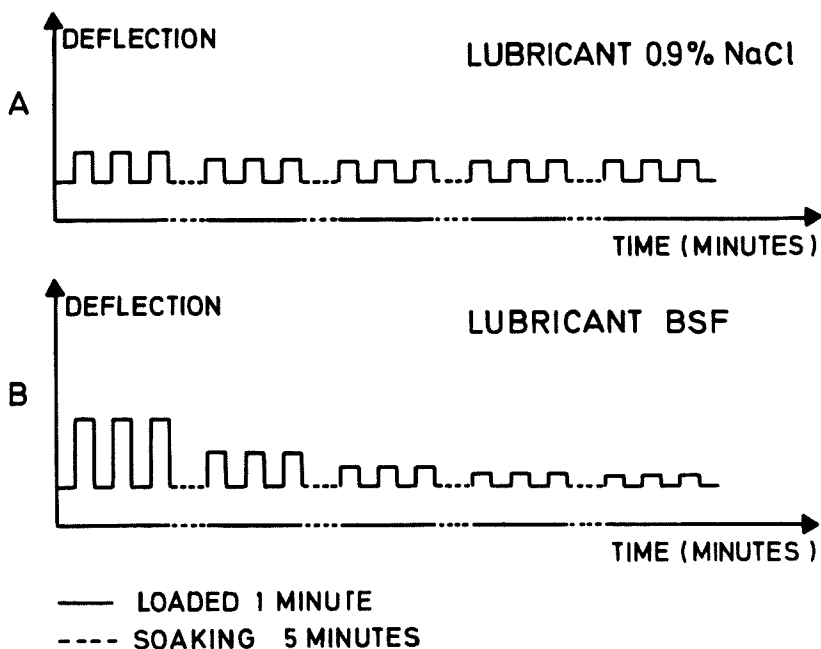


Figure 2. Diagram from a recorder used for determining the coefficient of friction and boundary lubrication for 0.9 per cent NaCl (curve A) and for bovine synovial fluid (curve B). The measurement of the coefficient of friction is recorded, with intervals of 5 min, unloaded, until equilibrium values are obtained.

with the slide (0.71), M is the total weight pressing the motion cylinder against the base plate (150), and X_1 is the total amplitude in square units achieved by the calibration when the weight is placed first over the one pulley and then over the other (16). K is calculated to be 0.0145.

MATERIAL AND METHODS

0.9 per cent NaCl and bovine synovial fluid (BSF) was used as a lubricant. The synovial fluid used in the experiments was from the hock joints of 2-year-old heifers (The Danish Meat Trade School, Roskilde). The fluid was taken in connection with slaughter and sterile precautions were exercised. Immediately after aspiration the fluid from the various joints was centrifuged for 20 min (3000 rev/min) and stored during the experimental period at 4° C. All measurements were carried out at room temperature (22° C).

To achieve boundary lubrication it is necessary to separate the rubbing surfaces for some minutes, thus making adsorption from the fluid possible. This was achieved by running each trial for 1 min loaded and 5 min soaking, then 1 min loaded and 5 min soaking until a constant value was obtained (Figure 2).

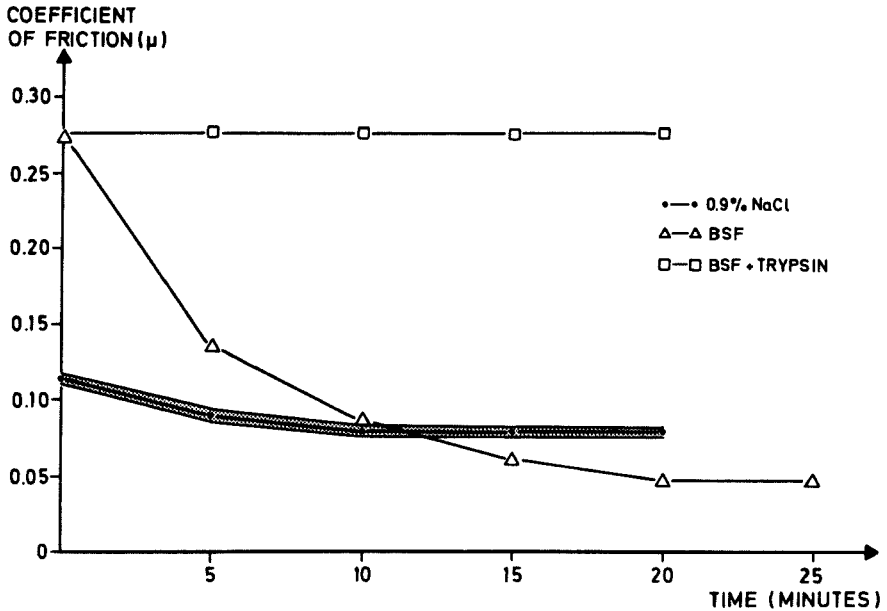


Figure 3. The diagram illustrates the decrease in coefficient of friction when 0.9 per cent NaCl and bovine synovial fluid are used as lubricant and the absence of boundary lubrication by bovine synovial fluid digested by trypsin. The marked area corresponds to the standard deviations of the values obtained by 0.9 per cent NaCl.

Numerous trials with saline and BSF as lubricant had to be made for standardization purposes before the results were reproducible.

During the standardization it was found that above all it was the condition of the rubber with regard to its cleanliness and tension which could effect a change in the results.

As a standard cleaning method for the rubber the following was found suitable: washing with Deconex 11® for 2 min, washing in running tap water for 5 min, rinsing in distilled water and air-drying. During the trials it was found that insufficient washing resulted in a decreased lubrication effect.

As changes in the tension of the attached rubber influenced the coefficient of friction in such a way that increased tension resulted in increased coefficient of friction, a standard method was used for stretching the rubber during the mounting.

As a control to ensure that the condition of the rubber was uniform during the different trials when BSF was used as a lubricant, every trial with BSF was preceded by a trial with saline and the same rubber, and after this trial washing in running tap water for 2 min and rinsing in distilled water. It was required that the results of the initial test with saline fell within some standard values based on 12 measurements with saline and using a new rubber every time (Figure 3). If the values of the initial test with saline fell outside the calculated standard area, then the rubber was renewed.

The slides used were ordinary microscope slides which were cleaned in the following way: First in 4/5 of 70 per cent alcohol and 1/5 of concentrated hydrochloric acid; next washing with distilled water and drying for 90 min at 90° C.

The following trials with BSF were carried out:

- 1) 12 trials with the BSF from one joint with a new rubber every time preceded by a trial with saline in order to examine if the results were reproducible.
- 2) Examination of individual differences in boundary lubrication by BSF from 10 hock joints from sound animals of the same age.
- 3) Investigation of changes in boundary lubrication by BSF from 10 hock joints after storage at 4° C. The measurements were made immediately after aspiration, and after storage for 2 days, 2 weeks and 2 months, respectively.
- 4) Examination of the effect of an admixture of trypsin on boundary lubrication by BSF. Trypsin crystalline, 7500–8000 BAEE units per mg (B.D.H. England) was used, 0.1 mg in 10 ml BSF in 10 min at 22° C.

RESULTS

As is shown in Figure 3 the measurements with saline and BSF as lubricant show a decrease in the coefficient of friction during the test period as a demonstration of boundary lubrication, the decrease being most pronounced with BSF as lubricant. The diagram shows also that equilibrium μ occurred earlier when saline was used (after 10–15 min) than when BSF was used (after 20 min). The addition of trypsin to BSF showed unchanged μ , pointing to the lack of boundary lubrication.

Table 1 shows the changes in μ when saline and BSF from the same and from different heifers were used as lubricants. As indicated in the table, the standard deviations in all three groups are low (below 0.0145 square units) thus being within the measurement error of the reading. The deviations were greatest in the group with BSF from different cases as lubricant.

Table 2 illustrates the changes in the lubricating effect during storage. As is shown in the table, it is not until after 2 months that a distinct change occurs in the form of a reduction of the lubricating effect as equilibrium μ shows a marked increase.

Table 1. Effects on coefficient of friction (μ) of boundary lubrication by saline and BSF.

Lubricant	Number of tests	Initial μ	Equilibrium μ
0.9 % NaCl	12	0.1160 \pm 0.0012	0.0787 \pm 0.0012
BSF same case	12	0.2667 \pm 0.0029	0.0399 \pm 0.0015
BSF different cases	10	0.2770 \pm 0.0044	0.0486 \pm 0.0044

Table 2. Effect of storage of synovial fluid at 4° C on coefficient of friction (μ).

Days after aspiration	Number of cases	Equilibrium μ
0	10	0.0486 \pm 0.0044
2	10	0.0515 \pm 0.0044
14	10	0.0501 \pm 0.0044
60	10	0.0870 \pm 0.0068

DISCUSSION

The most important function of the synovial fluid is to act partly as a nutrient and partly as a lubricant.

Various theories about how the lubrication takes place have been advanced (Dowson 1967). Boundary lubrication (Charnley 1959) caused by adsorption of macromolecules from the synovial fluid on the cartilage surface depends on the composition of the synovial fluid as well as on the properties of the cartilage surface.

By experiments with addition of enzymes (Wilkins 1968, Linn & Radin 1968) it was proven that boundary lubrication may be related to the protein component of the polysaccharide-protein complex of the synovial fluid. Addition of trypsin, which decomposes the protein, destroys the effect of boundary lubrication. Experiments with trypsin in the present work confirmed this fact. That boundary lubrication, in contrast to hydrodynamic lubrication, does not depend on the viscosity has been proven by admixture of hyaluronidase (Wilkins 1968).

In the design of the apparatus it was important to avoid the occurrence of hydrodynamic lubrication. This was ensured partly by making the apparatus oscillating and partly by the use of a thrust bearing (McCutchen 1972).

In order to achieve boundary lubrication the rubbing surfaces must be separated for some time. Owing to the macromolecules in the synovial fluid it takes some time before a state of equilibrium sets in. In the present work equilibrium values with BSF occurred after 20 min which is a longer time than that demonstrated with the experiments with saline.

In the present work the greatest emphasis was laid on standardization of the equipment. The rubbing surfaces used were glass slides and thin rubber. The condition of the rubber is decisive for the result (Sokoloff 1972). The trials proved that if the rubber were not cleaned sufficiently boundary lubrication either failed to materialize or was

decreased. Furthermore, changes in tension of the rubber altered the coefficient of friction. To ensure constant conditions, saline was consequently used as standard.

In the experiments with BSF it was found in some cases that the amplitude at the beginning of a cycle of motion was lower than after sliding had been established. This is in accordance with Linn (1967) who states that it is due to the fact that static friction is lower than dynamic.

Swanson (1973) has mentioned that equilibrium μ with synovial fluid as lubricant is only a little lower than with saline. He draws the conclusion that the function of the synovial fluid from a biomechanical point of view is to protect the cartilage against changes of the surface. This is in conformity with Simon (1971) who found that tryptic digestions greatly reduce the wear protective properties of the synovial fluid.

Linn (1968) found that the synovial fluid may be stored for a few days at 4° C without any changes occurring in the boundary lubrication. This is in accordance with the findings in the present study, in which changes occurring after storage for 0, 2, 14, and 60 days were investigated. Not until after storage for 60 days was a distinct decrease of the lubricating effect observed.

Individual variations in boundary lubrication, when synovial fluid from the same kind of joints was used and the animals were healthy and of the same age, could not be proven.

The conclusion drawn from the experiments is that the apparatus can be regarded as suitable for demonstration of boundary lubrication by synovial fluid, and that the results are sufficiently reproducible to be used for clinical studies of different joint diseases. By combining the present examinations with measurements of the viscosity (Reimann et al. in press) information may be derived about changes in the protein component as well as in the polysaccharide component of the synovial fluid.

SUMMARY

An account is given of an oscillatory rotating friction measurement apparatus which can be used for demonstration of boundary lubrication by synovial fluid when rubber and glass are employed as rubbing surfaces.

A technical description of the apparatus is given.

The greatest importance is placed on getting the apparatus to demonstrate reproducible results when saline and normal bovine synovial

fluid are used as lubricant. The greatest variations are caused by differences in the cleaning of the rubber and in its tension.

On the basis of bovine synovial fluid from ten different hock joints investigations were made of individual variations and changes occurring during storage at 4° C. The individual variations were found to be of no importance; a decrease in the lubricating effect was observed only after storage for two months. Addition of trypsin confirmed that boundary lubrication by synovial fluid can be related to the protein component.

The conclusion is that the apparatus is considered suitable for clinical investigations of boundary lubrication in connection with different joint diseases.

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REFERENCES

- Charnley, J. (1959) The lubrication of animal joints. In: *Symposium on bio-mechanics*, pp. 12-22 London, Institution of Mechanical Engineers.
- Dintenfass, L. (1967) Current status of joint lubrication. In: *Symposium on bio-mechanics*, pp. 142-145 London, Institution of Mechanical Engineers.
- Dowson, D. (1967) Modes of lubrication in human joints. In: *Symposium on bio-mechanics*, pp. 45-54 London, Institution of Mechanical Engineers.
- Linn, F. C. (1967) Lubrication of animal joints I. The arthrotripsometer. *J. Bone Jt Surg.* **49-A**, 1079-1098.
- Linn, F. C. (1968) Lubrication of animal joints II. The mechanism. *J. Biomech.* **1**, 193-205.
- Linn, F. C. & Radin, E. L. (1968) Lubrication of animal joints III. The effect of certain chemical alterations of the cartilage and lubricant. *Arthr. and Rheum.* **11**, 674-682.
- MacConaill, M. A. (1932) The function of intra-articular fibro-cartilage, with special reference to the knee and inferior radio-ulnar joints. *J. Anat. (Lond.)* **66**, 210-217.
- McCutchen, C. W. (1966) Boundary lubrication by synovial fluid: Demonstration and possible osmotic explanation. *Fed. Proc.* **25**, 1061-1068.
- McCutchen, C. W. (1972) Personal communication.
- Reimann, I., Stougaard, J. & Northeved, A. Measurement of the viscosity of synovial fluid. *Scand. J. Rheum.* (in press).
- Simon, W. H. (1971) Wear properties of articular cartilage in vitro. *J. Biomech.* **4**, 379-389.

Sokoloff, L. (1972) Personal communication.

Swanson, S. A. V. (1973) Lubrification dans les articulations synoviales. *Acta orthop. belg.* **39**, 33-42.

Wilkins, J. F. (1968) Proteolytic destruction of synovial boundary lubrication. *Nature (Lond.)* **219**, 1050-1051.

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