Development and Design of a Test Device

for Cartilage Wear Studies

by

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(ABSTRACT)

Articular cartilage is a material with the appearance of simplicity and uniformity, but the chemical and biological structure of this material is very complex and not yet known in every detail. Our knowledge of cartilage wear behavior is limited and needs to be enlarged. Knowledge in this area could be important for the prevention and treatment of degenerative joint diseases.

Within the framework of this thesis, a literature search focused on the key words joint lubrication and cartilage wear was conducted. The result of this search was that almost all studies and experiments which have been carried out to investigate tribological processes in synovial joints focused on friction behavior. Only a few tests dealing with cartilage wear were conducted. Most of the cartilage wear studies were carried out under exaggerated conditions which might change the wear mechanisms. Two studies were undertaken under conditions close to normal conditions occurring in natural joints; one in entire joints with a pendulum device, the other one with a cartilage-on-cartilage test system. The test devices used in these tests offered no or limited opportunities for the variation of the test parameters. Test parameters are, for example, the type of motion, applied load, velocity, variation of the velocity during each cycle, type of specimen, and test fluid composition.

In consideration of the findings of the literature search, it was decided to design a new test device providing the capability of measuring friction, wear, and displacement
due to wear and/or cartilage deformation. Furthermore, the new test device for cartilage wear studies, allows the variation of the above mentioned test parameters.
Acknowledgements

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Furthermore, I extend my thanks to the VPI & SU Biomedical Research Support Grant Committee for providing funds for the construction of the cartilage wear test device.

I also give special thanks to the men in the machine shop who built the device I designed. They often had to listen patiently in order to understand what I wanted to explain.
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<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>[mm]</td>
<td>width of the octagonal strain ring</td>
</tr>
<tr>
<td>d</td>
<td>[mm]</td>
<td>diameter of the upper specimen</td>
</tr>
<tr>
<td>h</td>
<td>[mm]</td>
<td>height of the lower specimen</td>
</tr>
<tr>
<td>hₘ</td>
<td>[mm]</td>
<td>minimum film thickness of the lubricant</td>
</tr>
<tr>
<td>l</td>
<td>[mm]</td>
<td>length</td>
</tr>
<tr>
<td>r</td>
<td>[mm]</td>
<td>mean radius of the octagonal strain ring</td>
</tr>
<tr>
<td>t</td>
<td>[mm]</td>
<td>thickness of the octagonal strain ring</td>
</tr>
<tr>
<td>v</td>
<td>[m/s]</td>
<td>sliding velocity</td>
</tr>
<tr>
<td>v₁</td>
<td>[m/s]</td>
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<td>distance</td>
</tr>
<tr>
<td>Symbol</td>
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<td>Explanation</td>
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<td>--------</td>
<td>------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>E</td>
<td>$[\frac{N}{m^2}]$</td>
<td>modulus of elasticity</td>
</tr>
<tr>
<td>$E'$</td>
<td>$[\frac{N}{m^2}]$</td>
<td>reduced modulus of elasticity</td>
</tr>
<tr>
<td>$E_1$</td>
<td>$[\frac{N}{m^2}]$</td>
<td>modulus of elasticity of material 1</td>
</tr>
<tr>
<td>$E_2$</td>
<td>$[\frac{N}{m^2}]$</td>
<td>modulus of elasticity of material 2</td>
</tr>
<tr>
<td>F</td>
<td>[N]</td>
<td>load applied vertically</td>
</tr>
<tr>
<td>G</td>
<td>[/]</td>
<td>gage factor for the strain gages</td>
</tr>
<tr>
<td>$P_f$</td>
<td>[N]</td>
<td>frictional force</td>
</tr>
<tr>
<td>R</td>
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<td>$R_2$</td>
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</tr>
<tr>
<td>T</td>
<td>[$^\circ$C]</td>
<td>temperature</td>
</tr>
<tr>
<td>U</td>
<td>$[\frac{m}{s}]$</td>
<td>average velocity of two discs</td>
</tr>
<tr>
<td>$U_1$</td>
<td>$[\frac{m}{s}]$</td>
<td>velocity of disc 1</td>
</tr>
<tr>
<td>$U_2$</td>
<td>$[\frac{m}{s}]$</td>
<td>velocity of disc 2</td>
</tr>
<tr>
<td>V</td>
<td>[V]</td>
<td>voltage</td>
</tr>
<tr>
<td>$\Delta V$</td>
<td>[V]</td>
<td>voltage difference</td>
</tr>
<tr>
<td>W</td>
<td>$[\frac{N}{mm}]$</td>
<td>applied load per unit width of the disc</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>[/]</td>
<td>constant</td>
</tr>
<tr>
<td>$\delta_{r,50}$</td>
<td>[mm]</td>
<td>deformation of the octagonal strain ring at $\Theta = 50^\circ$</td>
</tr>
<tr>
<td>$\delta_{r,90}$</td>
<td>[mm]</td>
<td>deformation of the octagonal strain ring at $\Theta = 90^\circ$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>[/]</td>
<td>strain in the octagonal strain ring</td>
</tr>
<tr>
<td>$\varepsilon_{50}$</td>
<td>[/]</td>
<td>strain in the octagonal strain ring at $\Theta = 50^\circ$</td>
</tr>
<tr>
<td>$\varepsilon_{90}$</td>
<td>[/]</td>
<td>strain in the octagonal strain ring at $\Theta = 90^\circ$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Explanation</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$[^{\circ}]$</td>
<td>angle</td>
</tr>
<tr>
<td>$\dot{\phi}$</td>
<td>$[\frac{1}{s}]$</td>
<td>angle velocity</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$[\frac{N\text{s}}{m^2}]$</td>
<td>viscosity of the lubricant</td>
</tr>
<tr>
<td>$\nu$</td>
<td>$[\text{]}$</td>
<td>Poisson's Ratio</td>
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1.0 Introduction

Tribology is the science dealing with the study of friction, wear and lubrication (Furey [1]). It includes the interaction of surfaces in relative motion. The conditions under which the motion takes place (applied load, sliding velocity, temperature, humidity, ...) can be very different. The characterization of solid surfaces includes both physical and chemical aspects.

The interdisciplinary nature of tribology becomes enlarged when the action and interaction of synovial joints is considered. The term “biotribology” could be used to describe biological lubrication processes as well as those involved in the action of synovial joints (Furey [2,3]). Besides physical and chemical aspects, the consideration of biotribology includes biological, biochemical, and medical aspects.

The human body is a highly sophisticated machine. From an engineering point of view, synovial joints are remarkable systems. They provide the basis of movement by allowing bones to articulate on one another with a minimum of friction and wear—being lubricated with synovial fluid. The relative motion between the cartilage surfaces in a synovial joint is very complex and can be characterized by a mixture of sliding and roll-
ing. The loads which occur in human joints are surprisingly high. For example, the resultant forces on the cartilage in a human hip or knee can reach two to three times the body weight in normal level walking.

Unfortunately, various joint diseases, causing pain, loss of freedom of movement, and instability, occur even among young people. One of seven Americans of all ages and half of those over 65 have some form of arthritis. Arthritis is an umbrella term for diseases affecting joints and connective tissue. Osteoarthritis--sometimes called degenerative joint disease--is the most common form of arthritis. Degenerative joint diseases are characterized by the deterioration and loss of articular cartilage, by the formation of new bone at the margins and the base of the joints, and by changes in the composition of the synovial fluid (Furey [4]). In osteoarthritis the disease focuses on the cartilage rather than on the synovial fluid and soft tissue. Cartilage in osteoarthritic joints is not able to withstand normal stress which occurs during life. Under stress, splitting of the cartilage can be observed. C. Norkin and P. Levangie [5] state that this causes increased friction on the surfaces.

Our knowledge of the biological lubrication processes as well as those involved in the action of synovial joints is too limited. More knowledge about these processes could lead to a better understanding how synovial joints function from the tribological point of view. This, conceivably, could lead to advances in the prevention and treatment of osteoarthritis, as well as in partial and total joint replacement.

The mechanisms of cartilage wear are not known. Very little work has been done in this area. It is suggested that several mechanisms such as adhesive wear, abrasive wear, and fatigue wear work together (Swanson [6]). Almost all studies carried out on synovial joint lubrication have dealt with friction behavior and not wear. It is commonly assumed that friction and wear go together, that is high friction means high wear and vice versa. But actually, high friction does not necessarily imply high wear and vice
versa. Friction can be defined as the resistance offered to the sliding of one solid body over another (Furey [1]). Wear is the progressive loss of substance from the operating surface of the body as a result of relative motion at the surface (Furey [1]). Furthermore, almost all scientists who have worked on the tribology of synovial joints considered the system solely from a mechanical or rheological point of view. In most cases, the biochemistry of these systems has been neglected.

An important point of interest is also whether there is a change in wear behavior when a degenerative joint disease occurs. Whether the changes in wear behavior, if there are any, are the result of changes in the lubrication properties of the synovial fluid or of changes in the nature of the cartilage is not known. Perhaps, it is possible to find a connection between the tribology in synovial joints and osteoarthritis.

The overall goal of the work is to develop and design a test device for biotribological systems with emphasis on the wear behavior and biochemical aspects of cartilage-on-cartilage systems. Cartilage wear tests of cartilage-on-cartilage systems have neither been undertaken with entire joints nor with cartilage specimens before. The necessity to learn more about synovial joints as tribological systems provides the motivation for the work.

The completed device will provide researchers with the opportunity of carrying out experiments with animal cartilage specimens. This device will help lay a foundation for continued research on friction, wear and lubrication of articular cartilage in synovial joints. Such research should shed light on mechanisms of cartilage friction, wear and lubrication.
2.0 Basic Approach and Objectives

It is hoped that the work on this research project will fill a gap in the understanding of the tribological processes in synovial joints. Basically, five objectives of this study were established:

1. To review the literature and to present a comprehensive overview of research undertaken in the area of tribological processes in synovial joints. The findings and background gained in this first step were supposed to provide information useful for the design of the test device for cartilage wear studies.

2. To find out the conditions under which cartilage wear experiments should be undertaken and to establish requirements for conditions which should be met in order to carry out experiments.

3. To decide on the design goals of a test device considering the test conditions found in step 2.
4. To carry out a detailed design of the device for cartilage wear tests.

5. To oversee the construction of the device.
3.0 Synovial Joints

The human body is a highly sophisticated machine. The components can perform a variety of postures and movements. The design of bones, joint structure and muscle function is different for different joint functions. A joint can provide animals and human beings either with mobility or with stability. The variety of different joint designs is incredibly large. This becomes obvious when the reader considers that there are more than two hundred bones in the human skeleton and that their size varies from cherry stone size of the distal phalanx in the little toe to a length of more than one foot of the femur of the thigh. The shape of the bones varies from flat to round and the contour from convex to concave (Norkin, Levangie [5]). Synovial joints are freely-moving, low frictional junctures characterized by minimal energy dissipation and minimal wear.

This chapter will give an overall view over joint structures and mechanisms including some information about the loads and velocities which can occur. Figure 1 shows a simplified picture of a synovial joint.
Fig. 1. Simplified Picture of a Synovial Joint (Furey [4]).
3.1 *Articular Cartilage*

In a natural joint, the bones are kept apart by a layer of articular cartilage which is a material with the appearance of simplicity and uniformity. But the chemical and biological structure of this material is very complex and not yet known in every detail. The biomechanical behavior of cartilage still needs to be investigated further. Cartilage is a highly specialized tissue. It is the hardest of the soft tissues, but it is not as hard as bone. The mechanical responses of this tissue vary with pathology, site and nature of loading. Because of its location and function cartilage has to meet a unique set of physical and mechanical requirements. The tissue is capable of maintaining its shape and original configuration under moderate stress of short duration (Van Mow, Lai, Redler [7]). Cartilage thickness varies from species to species, from joint to joint, and from area to area within the joint (Simon [8]). In large human joints such as the knee and hip, the cartilage is between 2 mm and 4 mm thick (Mechim, Stockwell [9]).

Cartilage consists of about 75 percent water which is contained in a network of collagen fibers, elastin fibers and high molecular weight compounds called proteoglycans. Collagen is a protein with a tensile strength which is close to that of steel (Widmann [10]). Collagen fibers can vary greatly in shape and size and they may be arranged in very different ways. They are not elastic, but some arrangements allow a certain amount of elastic deformation. Elastin is another protein. Elastin fibers have elastic properties which enable them to deform under an applied force and to return to their original shape after the removal of the force. Articular cartilage has no blood supply, no nerves and very few cells. It is nourished by synovial fluid which also acts as a lubricant (Ghadially [11]).
The distribution of cells and other cartilage constituents varies throughout the thickness of the cartilage. Therefore, a cartilage layer can be divided into four different zones parallel to its surface (see Fig. 2). This classification is based on Collins [12] and McCall [13]. It is presented in a comprehensive form by Meachim and Stockwell [9].

Superficial Zone: The cells are discoidal and both the cells and the collagen fibers are arranged parallel to the surface. This smooth zone helps to distribute applied forces. It occupies 5-10% of the total cartilage thickness.

Intermediate Zone: The cells are spheroidal and equally spaced. The fibers are coiled, and they form an open lattice work. This zone permits deformation and helps to absorb some of the forces. It occupies 40-45% of the total cartilage thickness.

Deep Zone: The cells are spheroidal. They are arranged in columnar groups of four to eight cells. The fibers form a tighter meshwork, and are predominately perpendicular to the surface. This zone occupies 40-45% of the total cartilage thickness.

Calcified Zone: In this zone only very few cells can be found, but it is heavily impregnated with crystals of calcium salts. Therefore, it is not elastic. This zone occupies 5-10% of the total cartilage thickness.
Fig. 2. The Zones of Adult Articular Cartilage (Meachim and Stockwell [9]).
The first three zones merge imperceptibly. A blue line called "tidemark" demarcates the Deep Zone from the Calcified Zone. The Superficial, the Intermediate, and the Deep Zones contain a certain amount of cavities termed "lacunae".

The surface of articular cartilage is gently undulating (see Fig. 3). Different scientists have offered different explanations for this phenomenon. I. C. Clarke [14,15] proposed that the surface irregularities are due to the contour created by collapsing lacunae close under the cartilage surface. Walker et al. [16] measured the topographical nature of the cartilage surface. They found a regular local periodicity in the undulation (distance from height to height 25-50 μm, amplitude 2-5 μm) and suggested that the undulation is due to the regular array of large collagen bundles with a diameter of 1-3 μm. Some scientists even suggest the undulations are due to scanning electron microscopy (SEM) artifacts.

It was mentioned before that articular cartilage consists of about 75 percent water. This causes problems for the SEM of articular cartilage. A special treatment is necessary to remove the water from the tissue and conserve its structure. One possible technique is described by Bloebaum and Wilson [17]. Their described ‘Method-2’ is a long and tedious process employing a glutaraldehyde fixative in a cacodylic acid buffer, osmium tetroxide treatment, thiocarbohydrazide, several washes and rinses with distilled water, and placement in absolute ethanol followed by critical point drying using CO₂.

3.2 Synovial Fluid

As in cartilage, the major constituent of synovial fluid is water. Synovial fluid is essentially a dialysate of blood plasma with added hyaluronic acid, polysaccharides, and
Fig. 3. Schematic Illustration of Surface Patterns of Cartilage (Mow, Lai, Redler [7]).

a) I. C. Clarke  
b) Walker et al.
other compounds (Swanson [6]). It is produced by the synovial membrane in the joint (see Fig. 1). The large hyaluronate molecules make synovial fluid thixotropic; that means, the viscosity varies inversely with the rate of shear. Therefore, the flow behavior of synovial fluid is non-Newtonian.

Normal synovial fluid appears as a clear, pale yellow viscous fluid. The amount of synovial fluid which is contained in a healthy natural joint is very small, e.g., less than 0.5 ml fluid in a human knee. But still, synovial fluid keeps the cartilage surfaces in the joint lubricated. Unsworth et al. [18] have shown that synovial fluid reduces friction in natural joints.

The performance of natural joints observed from a tribological point of view is impressive. Natural joints act under a wide range of conditions, e.g., under high loads at low speeds and at low loads at high speeds. They are expected to last for life (e.g., 60-70 years). The excellence of the lubrication under normal conditions is reflected in the low friction coefficient which typically lies in the range 0.003-0.015 (Dumbleton [19]).

3.3 Joint Types

Synovial joints can be classified anatomically and physiologically into three main categories on the basis of the motions which each particular joint can perform. Uniaxial, biaxial, and triaxial joints are distinguished (Norkin, Levangie [5]). They are constructed so that the relative motion between two bones is allowed around one, two, or three axes, respectively. The axis of motion is usually located near or in the center of the joint or in one of the involved bones.
In the human body two types of uniaxial joints can be found, namely the hinge joint and the pivot joint. A hinge joint is a joint that functions like a hinge of a door; it permits motion around a single axis. In a pivot joint, the two components are designed like a ring and a pivot; the pivot rotates in the ring. This also permits motion around a single axis only.

There are also two types of biaxial joints in the human body. The first type is the saddle joint. In a saddle, joint each joint surface is both concave and convex. These surfaces fit together like a rider on a saddle. The second type of biaxial joints is given by condyloid joints. Here, one joint surface is concave, while the other one is convex. Both joint surfaces slide over each other so that the joint motion takes place in two planes around two axes.

In the third category, triaxial, two joint types exist. Ball-and-socket joints are formed by a ball-like convex surface which fits into a concave socket. This arrangement permits motions around three axes (flexion-tension, abduction-adduction, rotation). Another joint type in this category is presented by plane joints. They permit gliding between two or more bones as well as rotation relative to each other. The carpal bones can be given as an example for this joint type.

3.4 Joint Motion

Motion occurs as a result of movement of joints relative to each other. The relative movement between joint surfaces can be described with the terms roll, slide, and spin. In general, a mixture of rolling, sliding, and/or spinning occurs in the joints. The combination of rolling, sliding and/or spinning is dependent upon the shapes of the joint
surfaces involved. The axes about which the performed motion occurs may not be fixed but may move during articulation (see Fig. 4). The axis of rotation at any particular moment during the motion is an instantaneous axis of rotation.

The loads on joints occurring during motion can be very different. In the human body, typical weight bearing joints are the hip, the knee and the ankle. It is often thought that only the joints of the legs are weight-bearing, but in fact those of the upper extremities also bear load. For example, the elbow has to carry up to 3.2 kN during maximal isometric efforts (Dumbleton [19]).

In natural joints, the relative motion is normally discontinuous and oscillating. The magnitude of the relative velocity can change greatly, even during one particular motion of the body. In addition, a reversal of the direction of the velocity often can be observed. That means that the value of the velocity is close to or equal to zero at this moment.

As an example, Fig. 5 illustrates the variation of the load and sliding velocity occurring in a human hip joint during the walking cycle. The angular velocity in [rad/s] and the joint load per body weight in [kg/kg] are shown above the time percentage of the walking cycle. A healthy human being makes approximately 90 steps per minute at normal walking speed. One walking cycle includes two steps. The conditions in a joint vary from person to person.

The loads vary from almost zero to three times body weight. The curve of the sliding velocity moves up and down very differently from the curve of the load ratio. Both curves have two peaks. The load curve has its highest peak after approximately 20 percent of the walking cycle. This peak is followed by a small valley and a smaller peak at 55 percent of the cycle. The angular velocity has its first peak at approximately 28 percent of the walking cycle. In the middle of the cycle, at 50 percent, the velocity reaches a minimum, after which it increases very rapidly to reach its maximum at 70 percent of the walking cycle.
Fig. 4. Instantaneous Axis of Rotation as a Function of the Position of the Joint [Dumbleton, 19].
Fig. 5. Hip Joint Forces per Body Weight and Angular Sliding Velocities over Percentage of Walking Cycle [Dumbleton, 19].
In Fig. 6, the author shows a diagram which illustrates the ratio of joint load/body weight to angular velocity in a human hip joint at different parts of the walking cycle. This diagram suggests that the most severe conditions from a tribological point of view occur after 50 percent of the walking cycle. At this point, the velocity has reached its minimum and the load is relatively high. Therefore, the lubrication of the joint may be critical at this point. In the regime of hydrodynamic lubrication, high loads and low velocities lead to thinner fluid films. Further information on hydrodynamic lubrication is given in Sec. 3.5.1.

3.5 Joint Lubrication

The active study of lubrication of engineering components has a history of about 100 years. Work in the specific field of natural joint lubrication began about 50 years ago. A definition of the term “lubrication” is given by Furey [1]. Lubrication is a process of reducing friction and/or wear (or other forms of surface damage) between relatively moving surfaces by the application of a solid, liquid, or gaseous substance (e.g., lubricant). Most mechanical bearings are lubricated hydrodynamically; in this regime, relative motion between two surfaces produce a wedge-shaped film of lubricant. The load is supported by the pressure generated in the lubricant due to relative motion, velocity, and geometry of the system.

Natural joints are probably not lubricated in this way, because their motion is discontinuous and more or less of an oscillating type as mentioned in Section 3.4. The relative velocity is usually small compared with the velocities in mechanical bearings.
Fig. 6. Ratio of Hip Joint Forces per Body Weight to Angular Sliding Velocity over Percentage of the Walking Cycle.
Natural joints also differ from machine bearings, because their articular surfaces are elastic and naturally moist. In natural joints, the lubricant is synovial fluid (see Sec. 3.2).

The existing literature on joint lubrication is, at best, confusing. More than two dozen different theories for the description of the lubrication mechanisms in artificial joints have been proposed by different investigators. The large number of diverse theories shows that our knowledge is minimal. Experimental as well as theoretical work has been done, but in most cases, the experimental results are not clear and not convincing. Examples of proposed mechanisms of joint lubrication are shown Table 1.

The purpose of the literature search done within the framework of this thesis was to become familiar with the research undertaken in the area of tribological processes in synovial joints. Special emphasis was put on cartilage wear studies. The attempt was undertaken to find out the strengths and weaknesses of the studies carried out. In the following section, the different studies are listed in the Tables 2-7 containing information such as the names of the scientists, year of publication, references, type of study, test systems, test fluids, loads, type of measurements, coefficient of friction, sliding velocities, and temperature of the environment. The studies are arranged in four groups and sorted according to the date of publication. The four groups are hydrodynamic/elastohydrodynamic lubrication, squeeze-film lubrication, boundary lubrication, and miscellaneous theories. The studies dealing with cartilage wear are treated in a separate discussion.

The first difficulty in approaching a systematic order was deciding which theories should be included. For some theories, this question is not easy to answer, because often the theories and especially the experiments conducted deal only indirectly with joint lubrication. For instance, some of the theories are more concerned with friction or the permeability of cartilage. The tables cannot be expected to be complete, since it was
Table 1. Examples of Proposed Mechanisms of Joint Lubrication (Furey [2]).

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Author</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hydrodynamic</td>
<td>MacConnail</td>
<td>1932</td>
</tr>
<tr>
<td>2. Boundary</td>
<td>Jones</td>
<td>1934</td>
</tr>
<tr>
<td>3. Hydrodynamic</td>
<td>Jones</td>
<td>1936</td>
</tr>
<tr>
<td>4. Boundary</td>
<td>Charnley</td>
<td>1959</td>
</tr>
<tr>
<td>5. Weeping</td>
<td>McCutchen</td>
<td>1959</td>
</tr>
<tr>
<td>7. Thixotropic/Elastic Fluid</td>
<td>Dintenfass</td>
<td>1963</td>
</tr>
<tr>
<td>8. Elastohydrodynamic (EHL)</td>
<td>Tanner</td>
<td>1966</td>
</tr>
<tr>
<td></td>
<td>Dowson</td>
<td>1967</td>
</tr>
<tr>
<td>9. Osmotic (Boundary)</td>
<td>McCutchen</td>
<td>1966</td>
</tr>
<tr>
<td>10. Squeeze-Film</td>
<td>Fein</td>
<td>1966</td>
</tr>
<tr>
<td></td>
<td>Higginson et al.</td>
<td>1974</td>
</tr>
<tr>
<td>11. Synovial Gel</td>
<td>Maroudas</td>
<td>1967</td>
</tr>
<tr>
<td>12. Thin-Film</td>
<td>Faber et al.</td>
<td>1967</td>
</tr>
<tr>
<td>13. Combination of Hydrostatic, Boundary and EHL</td>
<td>Linn</td>
<td>1968</td>
</tr>
<tr>
<td>15. Lipid</td>
<td>Little et al.</td>
<td>1969</td>
</tr>
<tr>
<td>16. Weeping + Boundary</td>
<td>McCutchen and Wilkins</td>
<td>1969</td>
</tr>
<tr>
<td></td>
<td>McCutchen</td>
<td>1969</td>
</tr>
<tr>
<td></td>
<td>Caygill and West</td>
<td>1969</td>
</tr>
<tr>
<td>17. Boundary</td>
<td>Freeman et al.</td>
<td>1970</td>
</tr>
<tr>
<td>18. Fat (or Mucin)</td>
<td>Roberts</td>
<td>1971</td>
</tr>
<tr>
<td>19. Electrostatic</td>
<td>Radin and Paul</td>
<td>1972</td>
</tr>
<tr>
<td>20. Boundary + Squeeze-Film</td>
<td>Unsworth et al.</td>
<td>1974</td>
</tr>
<tr>
<td>21. Mixed</td>
<td>Ling</td>
<td>1974</td>
</tr>
<tr>
<td>22. Imbibe/Exudate Composite Model</td>
<td>Mow et al.</td>
<td>1974</td>
</tr>
<tr>
<td>23. Complex Biomechanical Model</td>
<td>Dinnar</td>
<td>1974</td>
</tr>
<tr>
<td>24. Two Porous Layer Model</td>
<td>Reimann et al.</td>
<td>1975</td>
</tr>
<tr>
<td>25. Boundary</td>
<td>Unsworth, Dowson et al.</td>
<td>1975</td>
</tr>
<tr>
<td>26. Squeeze-Film + Fluid Film + Boundary</td>
<td>Eidelberg</td>
<td>1975</td>
</tr>
<tr>
<td>27. Finite Element Model</td>
<td>Rybicki</td>
<td>1977</td>
</tr>
<tr>
<td>28. Compliant Bearing Model</td>
<td>Swann et al.</td>
<td>1977</td>
</tr>
<tr>
<td>29. Lubricating Glycoproteins</td>
<td>Sokoloff et al.</td>
<td>1979</td>
</tr>
<tr>
<td>30. Structuring of Boundary Water</td>
<td>Kenyon</td>
<td>1980</td>
</tr>
<tr>
<td>31. Surface Flow</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
impossible to pay attention to every scientist who ever had worked on the topic of joint lubrication.

3.5.1 Hydrodynamic and Elasto-Hydrodynamic Lubrication

In hydrodynamic lubrication, the load is supported by the pressure developed due to relative motion and geometry of the system (Halling [20]). There is no contact between the surfaces. Friction is caused only by shearing of the lubricant. The film thickness is determined by the viscosity of the lubricant and the shear rate.

Since the lubricant has a certain viscosity, the moving surface drags it towards the thin end of the wedge, where there is less and less space for it. A pressure results in the lubricant, and this pressure supports the load. If the generated pressure is high enough to cause elastic deformation of the surfaces, the geometry of the lubricating film is modified. When in addition to the elastic deformation of the surfaces the variation of the viscosity of the lubricant as a function of pressure is considered, the mechanism is known as elasto-hydrodynamic lubrication.

Numerous investigators including Petroff, Tower, Reynolds, Sommerfeld and many others (Halling [20], Cameron [21]) have done work in the field of hydrodynamic lubrication. In the "rigid-isoviscous" regime for two discs rolling on each other, the so called Reynolds Equation is valid:

\[ h_o = 4.9 \cdot \left[ \frac{\eta U}{W} \right] \cdot R \]

where \( h_o \triangleq \) minimum lubricant film thickness
\( \eta \triangleq \) viscosity of the lubricant

Synovial Joints
\[ U \triangleq \text{average velocity of the two discs} \quad U = \frac{U_1 + U_2}{2} \]

\[ W \triangleq \text{applied load per unit width of the discs} \]

\[ R \triangleq \text{reduced radius of curvature} \quad \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \]

Besides the simple equation for the "rigid-isoviscous" regime, three other equations can be developed (Furey [1]). They consider either an elastic deformation of the solid bodies or a change of fluid viscosity due to high pressure or both of these factors:

**elastic-isoviscous:**

\[ h_o = 2.35 \cdot \left[ \frac{\eta U}{W} \right]^{0.6} \cdot \left[ \frac{W}{RE'} \right]^{0.4} \cdot R \]

**rigid-viscous:**

\[ h_o = 1.66 \cdot \left[ \frac{\eta U}{W} \right]^{2} \cdot \left[ \frac{\alpha W}{R} \right]^{2} \cdot R \]

**elastic-viscous:**

\[ h_o = 2.6 \cdot \left[ \frac{\eta U}{W} \right]^{0.7} \cdot \left[ \frac{\alpha W}{R} \right]^{0.54} \cdot \left[ \frac{W}{RE'} \right] \]

where \[ E' \triangleq \text{reduced modulus of elasticity} \quad \frac{1}{E'} = \frac{(1-v_1^2)}{E_1} + \frac{(1-v_2^2)}{E_2} \]

\[ v \triangleq \text{Poisson's Ratio} \]
\[ \alpha \triangleq \text{pressure-viscosity coefficient} \quad \frac{\eta}{\eta_0} = e^{\alpha - \beta} \]

The dimensionless term \[ \left( \frac{\eta U}{W} \right) \] is called the hydrodynamic factor. In addition to this, the elastic deformation factor \[ \left( \frac{W}{RE} \right) \] and the pressure-viscosity factor \[ \left( \frac{\alpha W}{R} \right) \] can be considered. The minimum film thickness \( h_m \) depends upon the viscosity \( \eta \) of the lubricant, the average velocity of the discs \( U \), the applied load \( W \), the radius \( R \) of curvature, and the modulus of elasticity \( E \). In Table 2, the group of hydrodynamic and elasto-hydrodynamic lubrication is presented by seven studies. In this group, theoretical work predominates. In some cases, existing theories of lubrication were theoretically applied to joint lubrication. Experiments were carried out by Jones [23, 24]. The other scientists investigated the problem of joint lubrication in purely theoretical studies. Jones used for his experiments an ingenious friction balance and a pendulum device. In both cases, he undertook cartilage-on-cartilage tests. Jones was probably the first scientist who undertook cartilage-on-cartilage tests. He used horse stifle joints and human finger joints and measured friction at different velocities. He lubricated his tests systems with synovial fluid and Ringer's Solution.

Most of the theoretical work done in the group of hydrodynamic/elasto-hydrodynamic lubrication dealt with the elasto-hydrodynamic regime. Dintenfass tried to find a model for the mathematical simulation of elasto-hydrodynamic lubrication in synovial joints. Tanner tried to explain experimental results found by Bell [25]. Bell measured the oil film thickness in an gelatine-on-glass system. The theory of hydrodynamic lubrication was considered by McConaill.
<table>
<thead>
<tr>
<th>Name of Investigator</th>
<th>Year</th>
<th>Test System Type or Study</th>
<th>Test Fluid</th>
<th>Load Type or Measurement</th>
<th>Type of Joint or Cartilage-on-Cartilage Type</th>
<th>Coeff. of Friction</th>
<th>Sliding Speed or Cycles per Min.</th>
<th>Temp. of Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>McCann, M. A.</td>
<td>1933</td>
<td>1932 Hydrodynamic</td>
<td>Synovial fluid, horse stifle joint</td>
<td>125N, 9.094 kg, 45.4 kg</td>
<td>Cartilage-on-cartilage (narrow intercarpal)</td>
<td>0.02</td>
<td>&quot;very low&quot;</td>
<td>&quot;varying&quot;</td>
</tr>
<tr>
<td>Jones, F. S.</td>
<td>1954</td>
<td>1953 Dynamic</td>
<td>Finger's Solution</td>
<td>125N, 9.094 kg, 45.4 kg</td>
<td>Cartilage-on-cartilage (narrow intercarpal)</td>
<td>0.02</td>
<td>&quot;very low&quot;</td>
<td>&quot;varying&quot;</td>
</tr>
<tr>
<td>Durand, L.</td>
<td>1954</td>
<td>1954 Elastic</td>
<td>Synovial fluid, horse stifle joint</td>
<td>125N, 9.094 kg, 45.4 kg</td>
<td>Cartilage-on-cartilage (narrow intercarpal)</td>
<td>0.02</td>
<td>&quot;very low&quot;</td>
<td>&quot;varying&quot;</td>
</tr>
<tr>
<td>Tamers, R. L.</td>
<td>1964</td>
<td>1964 Hydrodynamic</td>
<td>Finger's Solution</td>
<td>125N, 9.094 kg, 45.4 kg</td>
<td>Cartilage-on-cartilage (narrow intercarpal)</td>
<td>0.02</td>
<td>&quot;very low&quot;</td>
<td>&quot;varying&quot;</td>
</tr>
<tr>
<td>Medley, J. B.</td>
<td>1954</td>
<td>1954 Consultative</td>
<td>Synovial fluid, horse stifle joint</td>
<td>125N, 9.094 kg, 45.4 kg</td>
<td>Cartilage-on-cartilage (narrow intercarpal)</td>
<td>0.02</td>
<td>&quot;very low&quot;</td>
<td>&quot;varying&quot;</td>
</tr>
<tr>
<td>Dosshe, D.</td>
<td>1964</td>
<td>1964 Consultative</td>
<td>Finger's Solution</td>
<td>125N, 9.094 kg, 45.4 kg</td>
<td>Cartilage-on-cartilage (narrow intercarpal)</td>
<td>0.02</td>
<td>&quot;very low&quot;</td>
<td>&quot;varying&quot;</td>
</tr>
</tbody>
</table>

Table 2: Theories of Hydrodynamic and Elasto-Hydrodynamic Lubrication.
3.5.2 Squeeze-Film Lubrication

If two surfaces are forced together with a fluid film between them, the fluid will tend to flow out of the film. Therefore, with increasing time and under load, the thickness of the film will tend to decrease. If the load is applied intermittently and if the film is sufficiently viscous, the fluid film may persist for a time long enough to be useful. But after a certain time, the surfaces will come into direct contact. The regime of lubrication is called squeeze film lubrication. In Table 3, the studies dealing with squeeze-film lubrication are listed. In 1967, Fein [31] developed this model theoretically. A limitation of Fein's theoretical model must be seen by the fact that it ignores the permeability of cartilage to water and small solutes and the time-dependence of the deformation of the cartilage. Higginson and Norman [32] tried to prove Fein's theory experimentally by carrying out tests with artificial materials. They measured the pressure in the center of an oil film between a rigid disc and a porous elastic plane layer. During the measurements, the two surfaces approached each other. Rybicki [34] and Rohde [36] did also theoretical work on the model of squeeze-film lubrication.

3.5.3 Boundary Lubrication

A generally accepted definition of the term "boundary lubrication" has yet not been found. Boundary lubrication is often described as a condition of lubrication in which the friction and wear between the two surfaces in relative motion are determined by the surface properties of the solids and the chemical nature of the lubricant rather than its viscosity (Furey [1]). In the regime of boundary lubrication, a layer of molecular dimensions adheres to at least one of the two interacting surfaces by chemisorption,
### Table 3: Theories of Squeeze-Film Lubrication.

<table>
<thead>
<tr>
<th>Name of Investigator</th>
<th>Year</th>
<th>Theory</th>
<th>Test System</th>
<th>Cartilage or Joint Type</th>
<th>Test Fluid</th>
<th>Load</th>
<th>Type of Measurement</th>
<th>Coeff. of Friction</th>
<th>Sliding Speed or Cycles per min.</th>
<th>Temp. of Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fein, R. S.</td>
<td>1967</td>
<td>squeeze-film</td>
<td>theoretical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higginson, G. R.</td>
<td>1974</td>
<td>squeeze-film</td>
<td>device with rigid spherical disc on porous elastic plane layer</td>
<td>/</td>
<td>mineral oil</td>
<td>max. of disc = 4.8 kg, separation initial = 0.25 mm</td>
<td>pressure in the center of the oil film</td>
<td>1 / / /</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Norman, R.</td>
<td>1977</td>
<td>squeeze-film</td>
<td>theoretical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higginson, G. R.</td>
<td>1978</td>
<td>squeeze-film</td>
<td>theoretical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rohde, S. M.</td>
<td>1979</td>
<td>squeeze-film</td>
<td>theoretical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
physisorption, chemical reactions with or on the solid surfaces, or by mere interposition of a solid or other material. The most important factor in boundary lubrication is the chemistry of the tribological system—the contacting solids and total environment including lubricants. Although a considerable amount of research has been done on boundary lubrication, a complete understanding of this lubrication regime has not been achieved. Therefore, until now, a generally accepted definition of boundary lubrication has not been found. However, the largest group of proposed theories of synovial joint lubrication is the group of boundary lubrication theories (see Tables 4 and 5). This group is composed of 20 studies. Each study includes experimental work; none is purely theoretical. The scientists involved in this group represent different areas such as biology, chemistry, medicine, and engineering. Therefore, in many cases, their background and their theories are very different from each other. The number of scientists who have based their lubrication theory for synovial joints on boundary lubrication is relatively large, because most of the scientists just stated that their work had to be put into this group. Only Swanson et al. [45], Sokoloff et al. [51, 52], and Swann et al. [55] dealt with the biochemistry of the tribological systems. The other workers tried to explain different phenomena which they observed in their experiments. These phenomena did not necessarily deal with the biochemistry of the lubrication process.

Swanson et al. [45] measured friction at different loads and constant sliding velocity in a freely oscillating pendulum device. They used human hip joints in which the cartilage was treated to remove the fat. As lubricant they used treated and untreated synovial fluid. The purpose of the tests was to find which constituents of synovial fluid has a friction-reducing property.

Sokoloff et al. [51, 52] introduced a model for boundary lubrication of joint cartilage by synovial fluid based on data obtained from 'in vitro' friction tests using both cartilage and widely different artificial surfaces. The test systems were lubricated
<table>
<thead>
<tr>
<th>Name of Investigator</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Theory</th>
<th>Test System or Type of Study</th>
<th>Cartilage or Joint Type</th>
<th>Test Fluid</th>
<th>Load</th>
<th>Type of Measurement</th>
<th>Coeff. of Friction</th>
<th>Sliding Speed or Cycles per min.</th>
<th>Temp. of Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charnley, J.</td>
<td>1959</td>
<td>1959</td>
<td>boundary</td>
<td>apparatus for friction measurements in which entire joints can be fixed</td>
<td>human knee without menisci</td>
<td>synovial fluid</td>
<td>27-2670 N (static) ≤ 2.75-272.2 kg</td>
<td>friction</td>
<td>0.005-0.023</td>
<td>0.0-7.00 mm/s</td>
<td></td>
</tr>
<tr>
<td>McCutchen, C. W.</td>
<td>1962</td>
<td>1966</td>
<td>boundary</td>
<td>rubber on glass cartilage specimen against glass</td>
<td>/</td>
<td>soapy water</td>
<td>0.3 kg/m²</td>
<td>friction</td>
<td>0.003-0.1</td>
<td>10 cpm ≈ 11 mm/s</td>
<td></td>
</tr>
<tr>
<td>Linn, F. C.</td>
<td>1968</td>
<td>1968</td>
<td>boundary</td>
<td>pendulum device (called arthrotrometer) described by Linn [39]</td>
<td>dog ankle</td>
<td>bovine syn. fluid treated with hyaluronidase, trypsin or heparin</td>
<td>18.2 kg</td>
<td>friction</td>
<td>0.004</td>
<td>40 cpm</td>
<td>23°C</td>
</tr>
<tr>
<td>Wilkins, J. V.</td>
<td>1968</td>
<td>1968</td>
<td>boundary</td>
<td>rubber on glass</td>
<td>/</td>
<td>synovial fluid treated with hyaluronidase or trypsin</td>
<td>3.06 kg/m²</td>
<td>friction</td>
<td>0.01</td>
<td>(0-1) m/s</td>
<td>25°C 38°C</td>
</tr>
<tr>
<td>Swanson, S. A. V.</td>
<td>1969</td>
<td>1969</td>
<td>boundary</td>
<td>free oscillating pendulum device sensed by accelerometer</td>
<td>human hip joints, cartilage treated to remove fat</td>
<td>treated and untreated synovial fluid</td>
<td>9.0 kg</td>
<td>friction</td>
<td>0.005-0.024</td>
<td>60 cpm</td>
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</tr>
<tr>
<td>Radin, E. L. Swann, D. A. Weisser, V. A.</td>
<td>1971</td>
<td>1971</td>
<td>boundary</td>
<td>pendulum device (arthrotrometer)</td>
<td>entire bovine metatarsophalangeal joints</td>
<td>bovine syn. fluid treated with trypsin</td>
<td>113.5 kg</td>
<td>friction</td>
<td>0.0021-0.0079</td>
<td>40 cpm</td>
<td>23°C</td>
</tr>
<tr>
<td>Radin, E. L. Voul, T. L.</td>
<td>1971</td>
<td>1971</td>
<td>boundary</td>
<td>pendulum device (arthrotrometer)</td>
<td>entire bovine metatarsophalangeal joints</td>
<td>synovial fluid of the same animal</td>
<td>908.0 kg</td>
<td>friction, wear</td>
<td>0.0016-0.0028</td>
<td>40 cpm</td>
<td>23°C</td>
</tr>
<tr>
<td>Name of Investigator</td>
<td>Year</td>
<td>Theory</td>
<td>Test System or Type of Study</td>
<td>Cartilage or Joint Type</td>
<td>Test Fluid</td>
<td>Load</td>
<td>Type of Measurement</td>
<td>Coeff. of Friction</td>
<td>Sliding Speed or Cycles per min.</td>
<td>Temp. of Environment</td>
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<tr>
<td>Swann, D. A. Radin, E. I.</td>
<td>1972</td>
<td>boundary</td>
<td>pendulum device (arthrotesiometer)</td>
<td>entire bovine metatarsophalangeal joints</td>
<td>synovial fluid of the same animal</td>
<td>227.0 kg</td>
<td>friction, near</td>
<td>0.0016-0.0028</td>
<td>40 cp</td>
<td>23°C</td>
<td></td>
</tr>
<tr>
<td>Reiman, J. Stegengaard, J. Northved, A. Johnson, S. J.</td>
<td>1975</td>
<td>boundary</td>
<td>oscillatory rotating friction measurement apparatus, glass-rubber</td>
<td></td>
<td></td>
<td></td>
<td>friction</td>
<td>0.08-0.275</td>
<td>constant speed</td>
<td>22°C</td>
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<tr>
<td>Davis, H. T. Lee, S. L. Sokoloff, L.</td>
<td>1978</td>
<td>boundary</td>
<td>rotating disc on a flat ring under load, latex-glass system lubricated with synovial fluid</td>
<td>nasal septum of cows up to two years of age</td>
<td>synovial fluid from human knees with different degrees of osteoarthritis</td>
<td></td>
<td>friction</td>
<td>0.021-2.0</td>
<td>0.1-30 mm/s</td>
<td>35°C</td>
<td></td>
</tr>
<tr>
<td>Chappuis, J. Sherman, I. A. Neuman, A. W.</td>
<td>1982</td>
<td>boundary</td>
<td>measurement of interfacial tensions of biological materials</td>
<td>dog and pig cartilage</td>
<td>isotonic saline solution</td>
<td></td>
<td>surface tension of articular cartilage</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swann, D. A. Bloch, K. T. Swindell, D. Shore, E.</td>
<td>1986</td>
<td>boundary</td>
<td>cartilage-on-glass, device with rotating disc</td>
<td>phalangeal bone</td>
<td>human synovial fluid, bovine synovial fluid, versal buffer, 1XGP'</td>
<td></td>
<td>friction</td>
<td>0.92</td>
<td>10-38 mm/s</td>
<td></td>
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</tbody>
</table>
with synovial fluid. The model postulates that one protein of the synovial lubricating glycoprotein is adsorbed to the surface. According to the model, reduction in surface shear is accomplished by formation of hydration shells about the polar portion of the adsorbed lubricating glycoprotein. The adsorption of the glycoproteins creates a thin layer of viscous 'structured water' at the surface. Mutual electrostatic repulsion between charged polysaccharide moieties helps in separation of the adsorbed surface layers. During motion, the movement of water out of and into the cartilage is controlled by the hydration shells. Friction of a full disc rotating under load on a flat ring was measured as an angular displacement of the lower specimen. The motion applied was reversible rotation; that means, rotation in one direction, stop, rotation in the other direction.

Swann et al. [55] undertook friction measurements in cartilage-on-glass systems. In the test device, cartilage specimens were slid against a rotating disc. Swann et al. used bovine phalangeal bones and tested human and bovine synovial fluid as well as veronal buffer at a variety of sliding speeds and under a constant load. Furthermore, they had separated the so called LGP I (lubricating protogycan) from synovial fluid and showed that this substance has a friction-reducing property.

In the group of boundary lubrication, the variety of test systems used and the diversity of the objectives of the studies are very large. Therefore, a comparison of the test results is difficult.

In only three cases of the 20 studies of the group of boundary lubrication, parameters different from friction were measured. Radin and Paul [48] and Swann and Radin [49] measured friction and wear and Chappius et al. [53, 54] measured the surface tension of articular cartilage.
3.5.4 Miscellaneous Theories of Joint Lubrication

In Tables 6 and 7, seventeen studies of joint lubrication are listed; seven of these are theoretical, and ten are experimental. Five of the studies taken into consideration include experiments which are not related to a specific theory. The seventeen studies deal with eleven different theories. The theoretical studies are presented by the studies of mixed, boosted, and biphasic lubrication as well as by studies of the synovial gel theory, the protective membrane model, the two porous layer model and the finite element analysis.

The variety of test systems used in this group is very large. Rubber-on-glass systems lubricated with soapy water as well as pendulum devices using entire joints lubricated with synovial fluid can be found. Six studies out of seventeen actually dealt with cartilage test systems; four of them dealt with entire joints, two with cartilage specimens. In only four cases, parameters other than friction were measured. Faber et al. [62] measured the dissipative forces and the film thickness of synovial fluid in a living canine knee joint. Wear was measured by Simon [70], Clarke et al. [76], and Furey [2, 3]. The wear studies will be discussed in detail in Sec. 3.6. The study of Faber et al. was the only 'in vivo' study from all 49 studies taken into consideration.

3.5.4.1 Weeping Lubrication

The theory of weeping lubrication is based on two facts. First, cartilage is not rigid; therefore, applied load pressurizes the liquid in the cartilage. Second, cartilage is permeable. In 1959, McCutchen [58] started to work on the theory of weeping lubrication. He undertook friction measurements in a rubber-on-glass system at constant
### Table 6: Miscellaneous Theories of Joint Lubrication.

<table>
<thead>
<tr>
<th>Name of Investigator</th>
<th>Year</th>
<th>Theory</th>
<th>Test System or Type of Study</th>
<th>Cartilage or Joint Type</th>
<th>Test Fluid</th>
<th>Load</th>
<th>Type of Measurement</th>
<th>Coeff. of Friction</th>
<th>Sliding Speed or Cycles per min.</th>
<th>Temp. of Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>McCutchen, C. W.</td>
<td>1959</td>
<td>weeping</td>
<td>rubber on glass</td>
<td>/</td>
<td>soapy water</td>
<td>0.3 kg/m</td>
<td>friction</td>
<td>0.003-0.1</td>
<td>100 rpm ≈ 11 mm/s</td>
<td></td>
</tr>
<tr>
<td>Barnett, C. H.</td>
<td>1962</td>
<td>floating</td>
<td>special apparatus</td>
<td>dog ankle, human finger</td>
<td>synovial fluid</td>
<td>4-11 N</td>
<td>friction</td>
<td>0.018-0.030</td>
<td>free oscillating</td>
<td></td>
</tr>
<tr>
<td>McCutchen, C. W.</td>
<td>1966</td>
<td>osmotic</td>
<td>rubber on glass</td>
<td>/</td>
<td>synovial fluid</td>
<td>0.3 kg/m</td>
<td>friction</td>
<td>0.003-0.3</td>
<td>11 mm/s</td>
<td></td>
</tr>
<tr>
<td>Davies, D. W.</td>
<td>1966</td>
<td></td>
<td>/</td>
<td>/</td>
<td>synovial fluid</td>
<td>/</td>
<td>viscosity</td>
<td>/</td>
<td>/</td>
<td>33°C</td>
</tr>
<tr>
<td>Faber, J. J.</td>
<td>1967</td>
<td></td>
<td>entire joints in frictionometer</td>
<td>living knee joints of rabbits</td>
<td>synovial fluid</td>
<td>/</td>
<td>dissipative forces, friction, thickness of syn. fluid film</td>
<td>0.01</td>
<td>60 mm/s</td>
<td>body temperature</td>
</tr>
<tr>
<td>Dawson, D.</td>
<td>1967</td>
<td>mixed</td>
<td>theoretical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60 mm/s</td>
<td></td>
</tr>
<tr>
<td>Maroudas, A.</td>
<td>1967</td>
<td></td>
<td>1969</td>
<td>synovial gel</td>
<td>small particles of cartilage produced by grinding 100 μm thick specimens at low temperature</td>
<td></td>
<td></td>
<td></td>
<td>60 mm/s</td>
<td></td>
</tr>
<tr>
<td>Dawson, D.</td>
<td>1968</td>
<td>boosted</td>
<td>theoretical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60 mm/s</td>
<td></td>
</tr>
<tr>
<td>Wright, V.</td>
<td>1969</td>
<td></td>
<td>1969</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60 mm/s</td>
<td></td>
</tr>
<tr>
<td>Langfield, M. D.</td>
<td>1970</td>
<td></td>
<td>1970</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60 mm/s</td>
<td></td>
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<tr>
<td>Walker, P. S.</td>
<td>1965</td>
<td></td>
<td>Answorth, A.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60 mm/s</td>
<td></td>
</tr>
<tr>
<td>Ling, F. F.</td>
<td>1975</td>
<td>boosted</td>
<td>theoretical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60 mm/s</td>
<td></td>
</tr>
<tr>
<td>Radin, R. I.</td>
<td>1970</td>
<td>hydrostatic</td>
<td>device based on Lim's arthrostirometer</td>
<td>sagittal views of bone meta- tarsal phalangeal joints</td>
<td>synovial fluid</td>
<td>0-600 kg</td>
<td>friction</td>
<td>0.006-0.011</td>
<td>40 rpm</td>
<td>23°C</td>
</tr>
<tr>
<td>Paul, I. L.</td>
<td>1971</td>
<td>electrostatic</td>
<td>optical rubber-glass contact system</td>
<td>/</td>
<td>synovial fluid</td>
<td>film thickness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palousch, D.</td>
<td>1971</td>
<td></td>
<td>/</td>
<td>/</td>
<td>synovial fluid</td>
<td>50g/mm²</td>
<td>wear</td>
<td>/</td>
<td>60 mm/s</td>
<td></td>
</tr>
<tr>
<td>Simon, W. H.</td>
<td>1971</td>
<td>/</td>
<td>cartilage against rotating steel abrador</td>
<td>human patellar, canine humeral head</td>
<td>synovial fluid</td>
<td>200g/mm²</td>
<td>/</td>
<td>/</td>
<td>60 mm/s</td>
<td>25°C</td>
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</table>
Table 7: Miscellaneous Theories of Joint Lubrication (continued).

<table>
<thead>
<tr>
<th>Name of Investigator</th>
<th>Year</th>
<th>Theory</th>
<th>Test System or Type of Study</th>
<th>Cartilage or Joint Type</th>
<th>Test Fluid</th>
<th>Load</th>
<th>Type of Measurement</th>
<th>Coeff. of Friction</th>
<th>Sliding Speed or Cycles per min.</th>
<th>Temp. of Environment</th>
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</thead>
<tbody>
<tr>
<td>Mow, Van, C.</td>
<td>1973</td>
<td>biphasic</td>
<td>theoretical</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Torilli, D. A.</td>
<td>1979</td>
<td></td>
<td>pendulum device</td>
<td>human hip joint</td>
<td>synovial fluid, buffer solution</td>
<td>5000 N</td>
<td>friction wear</td>
<td>0.09-0.34</td>
<td>40 rpm</td>
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<tr>
<td>Lal, W. M.</td>
<td>1987</td>
<td></td>
<td>theoretical</td>
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<td>Mansour, J. M.</td>
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<td>Maki, A. F.</td>
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<td></td>
<td>theoretical</td>
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<td>Clarke, I. C.</td>
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<td>/</td>
<td>protective membrane model</td>
<td></td>
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<tr>
<td>Contini, R.</td>
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<td>/</td>
<td>theoretical</td>
<td></td>
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<td>Renedi, R. M.</td>
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<td>theoretical</td>
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<td>Eisenfeld, J.</td>
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<td>theoretical</td>
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<td>Linnar, U.</td>
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<td>/</td>
<td>theoretical</td>
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<tr>
<td>Eidelberg, B. E.</td>
<td>1975</td>
<td>/</td>
<td>theoretical</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Forsey, M. J.</td>
<td>1986</td>
<td>/</td>
<td>cartilage on stainless steel</td>
<td>bovine synovial joints</td>
<td>bovine syn. fluid, buffer saline, reference + hyaluronic acid, reference + HA fraction, reference + protein fraction, reference + Swan's LGP I, distilled water</td>
<td>53.4 N 5.44 kg</td>
<td>wear</td>
<td>40 rpm 8.5 mm/s</td>
<td>25°C</td>
<td></td>
</tr>
</tbody>
</table>
loads and velocities using soapy water as a lubricant. In 1975, C. W. McCutchen [56] drew a bottom line and suggested that the liquid in the cartilage would flow to the rubbing surfaces under pressure (see Fig. 7a). Therefore, the area of contact between the cartilage surfaces decreases. The pressure in the fluid carries the applied load causing no friction. The pressure distribution within the cartilage is given by the isobars in Fig. 7b. When the load is removed and the cartilage surfaces are separated, the cartilage layers expand and draw in the fluid as illustrated by the flow arrows and isobars in Fig. 7c.

3.5.4.2 Mixed Lubrication

The theory of mixed lubrication is set up out of a combination of two different theories. Therefore, it is questionable if it should be considered as a new theory by itself. In 1967, D. Dowson [631] introduced this purely theoretical model of lubrication. He stated that a natural joint is lubricated in low speed ranges by boundary lubrication and in high speed ranges by hydrodynamic lubrication.

3.5.4.3 Boosted Lubrication

In the theory of boosted lubrication, it is stated that the approach of two cartilage surfaces is followed by a sequence of events. When two cartilage surfaces lubricated by synovial fluid approach each other, the first contact will take place between the peaks of the surfaces. As the surfaces are pressed closer together, the area of contact between the elastic cartilage will increase and the load will be accommodated by this contact. In boosted lubrication, it is assumed that pools of trapped synovial fluid form
Fig. 7. Weeping Lubrication (McCutchen [56], Fig. taken from [39]).

a) flow towards the rubbing surfaces
b) pressure distribution
c) separation and re-entry of fluid
in the depressions in the cartilage surfaces in the interface between the two surfaces (see Fig. 8). The applied load pressurizes the trapped fluid. The water contained in the pressurized fluid will escape through the porous cartilage to lower pressure regions. The synovial fluid in the trapped pools becomes enriched; that means that the concentration of the large hyaluronic acid molecules will increase since the low viscosity constituents of synovial fluid escape through the cartilage. The trapped pools will give increased resistance to further approach of the cartilage surfaces. This theory was first developed by Walker et al. [16]. It is based on the idea of ultrafiltration by A. Maroudas [64]. F. F. Ling [67] tried to develop this theory further.

3.5.4.4 Electrostatic Lubrication

This theory states that synovial fluid gives each cartilage surface a high electrostatic charge density. Molecules of the synovial fluid are adsorbed by the cartilage surfaces. The surfaces are kept apart by short range electrical repulsive forces. A. D. Roberts [69] developed this theory and stated that there need not be any contact at all between the adsorbed molecules. He undertook experiments with a rubber-glass contact system measuring the film thickness of synovial fluid as a lubricant.

3.5.4.5 Biphasic Lubrication

Cartilage consists of liquid and solid phase components. The biphasic lubrication theory states that the liquid phase of cartilage is exuded into the inlet zone of the contact region during sliding. In the exit zone it is imbibed by the cartilage. This produces a liquid flux into the gap between the cartilage surfaces. In the development
Fig. 8. Boosted Lubrication (Walker et al. [16], Fig. taken from McCutchen [39]).
of this theory a number of scientists were involved; C. Van Mow, D. A. Torzilli, W. A. Lai, A. F. Mak and J. M. Mansour [71, 72, 73, 74, 75].

3.5.4.6 Mucin Gel Theory

It was proposed by A. Maroudas [64] that when two cartilage surfaces approach each other, the liquid in the film will escape by flowing into the cartilages and then tangentially through them, as well as by flowing between the rubbing surfaces (see Fig. 9). As the gap between the two cartilage surfaces become smaller, the fluid film also becomes thinner. Finally, one point will be reached where only water can escape through the gap between the surfaces. The long-chain molecules in the synovial fluid are too large to escape. Loss of fluid into the cartilages raises the mucin concentration in the gap between them. The concentrating process ceases when the osmotic pressure of the mucin equals the bearing pressure. According to this concept, the "mucin gel" can carry the bearing load.

3.5.5 General Comments and Discussion Focused on Joint Lubrication

In the Tables 2-7, 49 studies of joint lubrication are presented. 63 references were selected from the literature. Table 8 summarizes and presents statistical information about the types of studies included in the Tables 2-7. On the vertical axis, the table shows the groups of theories in which the studies are sorted. On the horizontal axis, the table shows the type of study, experimental or theoretical. The experimental studies are divided into studies investigating friction and studies investigating wear. Furthermore, a distinction is made between experiments with entire joints and experiments with
Fig. 9. Mucin Gel Theory (Maroudas [64], Fig. taken from McCutchen [39]).
cartilage specimens. The numbers in the boxes do not sum up to the total number of studies taken into consideration because the table does not show the experimental studies dealing with materials different from cartilage and studies in which neither friction nor wear was measured. But in the column under 'Number of Studies', the total number of studies is presented including the studies dealing with materials different from cartilage. Furthermore, in the Tables 2-7, two studies occur in which both friction and wear were measured (Radin and Paul [48], Swann and Radin [49]). These two studies are counted twice for Table 8.

A fact which attracts attention when the Tables 2-7 are examined is that not all listed experiments were carried out with cartilage. In eight studies, materials different from cartilage were used. In three cases, test systems composed of rubber and glass were used. Two other investigators used a latex-glass system or a teflon-glass system. In general, investigators who experimented with these special systems, not looking at cartilage, set up a theory and tried to prove it in special chosen simpler systems. After this phase of work, they tried to draw conclusions for the lubrication of cartilage or entire joints from the results of the experiments with completely different systems. Points like this must be considered very carefully, because some conclusions drawn from them might be valid, but other conclusions might be too hypothetical. It must always be taken into account that natural cartilage is an extremely complex material.

The studies which are considered purely theoretical are of course not supported by experimental evidence. A comparison of test results obtained in experimental studies is sometimes very difficult because of the large variety of test systems and test devices used. For example, thirteen investigators undertook experiments with devices using entire joints and eight with devices using cartilage specimens. Usually, a cartilage specimen is a piece of bone with one end covered with a layer of cartilage. For experiments with cartilage specimens, the situation for a comparison of the test results of
Table 8. Statistical Information about the Types of Studies Presented in the Tables 2-7.

<table>
<thead>
<tr>
<th>Type of Study</th>
<th>Number of Studies</th>
<th>Experimental Studies</th>
<th>Theoretical Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Friction</td>
<td>Wear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Entire Joints</td>
<td>Specimens</td>
</tr>
<tr>
<td>Hydrodyn. and EHL</td>
<td>7</td>
<td>/</td>
<td>2</td>
</tr>
<tr>
<td>Squeeze-Film Lubr.</td>
<td>5</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Boundary Lubrication</td>
<td>20</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Different Theories</td>
<td>17</td>
<td>/</td>
<td>3</td>
</tr>
</tbody>
</table>

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different scientists is acceptable, although the shapes of the specimens differ and therefore, the areas of contact vary from study to study. Most investigators using cartilage specimens initiated a relative sliding motion between a specimen and an artificial and flat surface. The systems were lubricated with different fluids: synovial fluid, Ringer's Solution, buffer, and artificial fluids. The applied loads were varied in the range of $(0.3 - 5) \times 10^4$ N/m$^2$.

For experiments with entire joints, a variety of different devices was used. The two devices used most often are pendulum devices. One of them is a device called arthrotripsometer (coming from old Greek: arthro ($\alpha \rho \theta \rho \omicron \upsilon$) meaning joint, tripso ($\tau \rho \iota \phi \omicron \upsilon$) meaning friction, meter ($\mu \epsilon \tau \rho \omicron \upsilon$) meaning measure). The arthrotripsometer is an apparatus for sensing and recording the instantaneous frictional properties and deformations of articular cartilage in 'in vitro' tests under conditions simulating human locomotion. The arthrotripsometer directly measures the frictional forces generated at the articular surfaces of a dog ankle under load as the talus oscillates through a fixed angle of 36.2 degrees. The second device for experiments with entire joints is the gravitational or Stanton Pendulum, a spring-loaded pendulum. Clarke, Contini and Kenedi [76] (Table 7) used a third type of pendulum device. This device is designed for tests with the human hip joint. It is loaded by weights and driven by a DC-motor. The applied loads in the test system with entire joints vary in the range of 0-100 kg.

The pressures resulting from the loads applied to a biotribological test system certainly depend upon the areas of contact in the systems. For tests with entire joints, the area of contact cannot be determined. The pressure values given by the investigators for tests with entire joints and with cartilage specimens vary from $0.3$ kg/m$^2$ to $3300$ kg/m$^2$. Unfortunately, it is not possible to bring all given values and units of the applied loads or resulting pressures into the same form because often the area of contact is given. Therefore, a comparison of the values is difficult or not impossible. Further-
more, in a number of cases, the test conditions under which the tests were carried out are not given in the literature. Sometimes, information about either the sliding velocity or the environmental temperature is missing. The sliding velocity is given in mm/s or in cycles/minute (cpm). In most cases, when the number of cycles per minute is given the sliding distance per cycle is not given. Therefore, the actual average sliding velocity cannot be calculated. Only some studies give information about the variation of the velocity during one cycle. The range of velocities used in the studies is 0-60 mm/s. The maximal number of cycles per minute is 60.

From the 49 studies taken into consideration, parameters other than friction were measured in only ten cases. Looking into it in detail, Higginson and Norman [32, 33] measured the pressure in the center of an oil film (Table 3); Chappius, Sherman and Neuman [53, 54] measured the surface tension of cartilage (Table 5); Davies [61] investigated the changes of viscosity of synovial fluid (Table 6); Faber, Williamson and Feldman [62] tried to measure the film thickness of the synovial fluid in a living rabbit joint (Table 6), and Roberts [69] investigated the film thickness (Table 6). From the five above mentioned studies, three dealt with biological materials, two with artificial materials.

In five other studies, cartilage wear was measured. Radin and Paul [48] (Table 4) and Swann and Radin [49] (Table 5) used the arthrotripsometer mentioned above with entire bovine joints. Clarke, Contini, and Kenedi [76] (Table 7) used the third type of pendulum device mentioned before and carried out there experiments with human hip joints. Furey [2, 3] (Table 7) conducted experiments with cartilage specimens on highly polished stainless steel. The fifth investigator, Simon [70] (Table 6), tried to investigate the influence of different constituents of synovial fluid on cartilage wear by abrading cartilage with a rotating steel abrader. This type of test is to be considered very care-
fully because in normal life cartilage is never exposed to such severe operation conditions. Cartilage wear will be discussed in detail in Sec. 3.6.

The preceding two paragraphs show that only a small number of investigators involved with the processes of joint lubrication measured other parameters than friction. Most scientists undertook only friction measurements and tried to evaluate the tribological systems in synovial joints by only taking friction into account. This reflects an incomplete consideration of the tribological processes in synovial joints. Lubrication is defined as a process of reducing friction and/or wear (or other forms of surface damage) between relatively moving surfaces by the application of a solid, liquid, or gaseous substance (Furey [1]). Therefore, for the evaluation of a tribological system in natural joints, it is necessary to consider friction, wear, and the environmental conditions under which the systems act. At this point, it is important to know that friction and wear are two different phenomena. When friction is high, it is not necessarily true that wear is high too, and vice versa. For this reason, it is really necessary to find out more about the wear behavior of cartilage.

Another important point which becomes obvious when analyzing the tables is that almost all workers consider the lubrication processes of an synovial joint more or less as a mechanical or rheological problem. Most workers do not pay attention to biochemical aspects. Swanson et al. [45], Sokoloff et al. [51, 52], Swann et al. [55], and Furey [2,3] are exceptions.

3.5.6 Cartilage Wear

In the preceding section, it was mentioned that most of the investigators working on lubrication processes in synovial joints probably did not know about the difference
between friction and wear or simply assumed that friction and wear go together. Another possible reason why so little work has been done in the area of cartilage wear is that wear experiments with cartilage systems are difficult.

In 1978, C. W. McCutchen [39] stated, for example, that in cartilage test systems wear must be tremendously accelerated, compared to its very low rate in nature, if any results are to be obtained within a reasonable time span. This statement does not reflect the author’s opinion. Under normal conditions, the wear rate in cartilage-on-cartilage systems is probably very low. But today, techniques are available to visualize and measure very low rates of wear. For example, the observation of cartilage with a scanning electron microscope (SEM) using a special technique introduced by Bloebaum and Wilson [17] after the wear experiment provides the opportunity to make the surface damage due to wear visible. Another possibility to figure out the amount of cartilage wear occurring during a test is the analysis of the hydroxyproline content of the lubricant as well as of the wear debris. Since the content of hydroxyproline is constant throughout the whole cartilage layer, it can be used to measure the extent of wear of articular cartilage. Approximately ten percent of the hydroxyproline of the wear debris is dissolved in the lubricating fluid. The technique for the analysis is described by Lipshitz, Etheredge III, and Glimcher [82]. It is developed by Woessner, Jr. [83]. This technique is very sensitive and provides the possibility to determine very low rates of wear.

In the preceding section, it was also mentioned that five of the studies taken into consideration dealt with cartilage wear. In the following, these studies will be introduced in more detail.

Simon [70] undertook cartilage wear tests in which articular cartilage from human patellae and canine femoral heads was abraded by a stainless steel rotary file. The depth of the penetration with time and wear was measured. Furthermore, the wear
debris was collected and weighed. The abrader was run backwards at 120 rev./min. Running forward, the file cut through the cartilage in a matter of seconds. Running backward, the negative rake of the cutting edges prevented clean cutting. Grooves in the file allowed circulation of lubricant between the cartilage and the abrader. A slow and steady drip of a physiological saline solution or synovial fluid was directed onto the cartilage-abrader interface. From here, the fluid dripped on a filter where it was gathered. The filter and the debris were washed with distilled water to remove salt before weighing. In the cases of lubrication with synovial fluid, the wear debris was washed with 0.2 % testicular hyaluronidase to prevent the pores from being plugged by hyaluronate.

Wear was measured in terms of the distance the abrader had moved into the cartilage or by the weight of the accumulated debris. The tests were undertaken in a wet atmosphere at body temperature (37°C). These conditions were produced by mixing steam and air.

Simon examined the following points:

1. The effect of synovial fluid versus saline solution as a lubricant.

2. The effect of osteoarthritic fibrillation versus intact human patella cartilage.

3. The effect of age.

4. The effect of various agents that might alter the physical texture of cartilage.
The experiments conducted by Simon must be considered critically because it is difficult to transfer the results to the tribological processes in natural joints. Simon found out that synovial fluid protects articular cartilage against wear better than the saline solution.

Radin and Paul [48] tested the sagital halves of bovine metatarphalangeal joints lubricated with veronate buffer in a arthrotripsometer. Veronate buffer was used instead of synovial fluid because earlier tests had shown that at the loads used in these tests, the friction-reducing property of synovial fluid was negligible. Joint wear was evaluated by gross and histologic inspection including microscopic observation. Radin and Paul ran tests for up to 500 hours ($\approx 1.2 \cdot 10^4$ cycles of oscillation) under a load of 454 kg ($\approx 4450$ N) without causing significant wear. But they found that the joints started to wear out after 100 hours ($\approx 24000$ cycles of oscillation) when the system was loaded steadily with 226 kg ($\approx 2250$ N) and briefly, once a cycle, with another 226 kg when the sliding was stopped temporarily. The additional load was applied for two seconds. Within 24000 cycles peripheral fissures appeared. After 48000 cycles, the central area of cartilage began to roughen. After 72000 cycles, the second zone (intermediate zone) became exposed and after 192000 cycles the bone was exposed.

The cartilage damage observed by Radin and Paul results from the application of the impulsive forces rather than from relative motion under load. The constant load of 454 kg is high in comparison to the loads occurring under normal conditions. It is about two-thirds of the load which causes crushing of the cancelous bone of a joint.

The measurements undertaken by Swann and Radin [49] focused on friction rather than on wear. They tried to compare lubrication by synovial fluid with lubrication by veronal buffer at a variety of loads. For their tests, they used bovine metatarphalangeal joints in a arthrotripsometer. They found that synovial fluid loses its lubrication ad-
vantages over buffer at high loads of about 500 kg. Swann and Radin evaluated joint wear by gross and histologic inspection including observation with a microscope.

Clarke, Contini, and Keneti [76] did experiments to investigate friction and wear characteristics with human hip joints in a pendulum device. This device was equipped to carry weights and load the test system with 209 kg in increments of 18 kg. The frictional characteristics were measured when the pendulum device was freely oscillating. The amplitude of the pendulum oscillation was monitored using a rectilinear potentiometer. The coefficient of friction was determined from the descending values of the amplitudes.

For the wear experiments, a 1/6-hp electric motor drove an eccentric crank which oscillated the pendulum. The frequency of oscillation was matched to frequencies under normal conditions. After the wear tests, the cartilage surfaces were observed with a SEM to observe wear.

The objectives of these cartilage wear studies were:

1. To establish an experimental lubrication and wear model which could be related to published data on joint frictional characteristics.

2. To use the SEM to detect whether there are changes visible on the articular surfaces with regard to the presence or absence of a lubricant.

3. To use the SEM to detect whether the model produced cartilage disruption and the nature of its progression.
To achieve an acceleration of the wear process, joints were run "dry". The results of these wear experiments were less severe than anticipated. Wear was produced after seven to eight hours operation and was evident as fissuring and flaking of the surface layer. The fissuring followed the orientation of the fibrillar layers. It was predominantly perpendicular to the joint motion. The disruption occurred at sides where osteoarthritic damage had been detected clinically.

M. J. Furey [2, 3] carried out experiments measuring wear in cartilage-on-stainless-steel systems lubricated with fluids composed of different constituents. The main objective of his study was to determine whether fluid composition influences the type of damage, wear, or change in cartilage surface structure in 'in vitro' wear tests. Another point of interest was the comparison of SEM results with previous cartilage wear results. For his tests, Furey used bovine cartilage plugs with a diameter of 5.7 mm. These plugs were prepared with a technique described by Lipshitz and Glimcher [84]. They were slid against a highly-polished stainless steel plate at an applied load of 53.4 N (5.44 kg), resulting in an average pressure of $2.1 \times 10^5$ kg/m$^2$ ($\approx 2.1$ MPa). Each test was carried out for four hours at 40 cycles per minute, resulting in a total of 9600 cycles. The pathway of the plugs on the stainless steel plate had the shape of an arc. The test conditions and the test fluids used are summarized in the Tables 9 and 10.

For the analysis of Furey's study, two different techniques were employed, the analysis of the 4-hydroxy proline content in the cartilage wear debris and the fluid as well as the observation with the SEM. The first mentioned analysis requires a sequence of steps described by Lipshitz et al. [82]. The frozen samples were thawed. Then, they were dialyzed, lyophilized, and hydroxylized. The procedure ended with a hypro determination in a cationic exchange HPLC column. The technique for the observation of the cartilage plugs with the SEM is already briefly described in Sec. 3.1.
Table 9. Test Conditions of the 'In Vitro' Cartilage Wear Experiments undertaken by Furey [2, 3].

<table>
<thead>
<tr>
<th>Contact Geometry</th>
<th>Flat-on-flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Articular Cartilage</td>
<td>Bovine (medial femoral condyle)</td>
</tr>
<tr>
<td>Cartilage Plug Diameter</td>
<td>5.7 mm</td>
</tr>
<tr>
<td>Applied Load</td>
<td>5.44 kg</td>
</tr>
<tr>
<td>Average Pressure</td>
<td>2.1 MPa</td>
</tr>
<tr>
<td>Traverse</td>
<td>6.35 mm</td>
</tr>
<tr>
<td>Cycles per Minute</td>
<td>40</td>
</tr>
<tr>
<td>Fluid Temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>Test Duration</td>
<td>4 h</td>
</tr>
<tr>
<td>Total Cycles</td>
<td>9600</td>
</tr>
</tbody>
</table>
Table 10. Test Fluids used in 'In Vitro' Cartilage Wear Experiments undertaken by Furey [2, 3].

1. Bovine synovial fluid
2. Buffer saline reference solution
3. Reference + hyaluronic acid (HA)
4. Reference + HA fraction from bovine synovial fluid
5. Reference + protein fraction from bovine synovial fluid
6. Reference + Swann's LGP-I (lubricating glycoprotein)
7. Distilled water
8. None (no test fluid added)
The results found by Furey reflected that synovial fluid is a lubricant which protects articular cartilage against wear. The biochemical composition of synovial fluid has a significant effect on cartilage wear and damage.

The introduction of the five cartilage wear studies showed that Radin and Paul as well as Clarke et al. observed wear under very severe conditions. This fact requires a very critical consideration of the test results because it is possible that under such extreme conditions the wear mechanisms are quite different from those occurring under normal conditions. In both cases mentioned above, it is probable that the mechanisms are not the same. In the experiments undertaken by Simon, there was no attempt made to simulate normal conditions occurring in natural joints. Therefore, it is questionable how these results relate to lubrication processes in natural joints. Only Swann and Radin as well as Furey tried to undertake tests under conditions close to normal conditions. Normal conditions are the conditions which occur in healthy synovial joints during life. Swann and Radin used the arthrotripsometer. Therefore, the motion involved in the tests was the oscillating motion of the pendulum and the variation of the sliding velocity during each cycle was fixed. The applied load was variable. In Furey's tests, the motion involved was fixed to a motion on an arc. Furey used a fixed load and a purely harmonic variation of the velocity during each cycle.

Reviewing the five cartilage wear studies, the author found that the variations of test parameters was limited in the studies undertaken. Furthermore, she found that cartilage-on-cartilage wear studies under normal conditions were never undertaken before. At this point, the decision was made to design a test device for cartilage wear studies with the possibility of varying the loads applied and the type of motion involved. The device should also provide the possibility of determining the variation of the velocity during each cycle and of determining the value of the speed. The possibility of controlling environmental data such as humidity and temperature should also be
included. Finally, for a completion of the picture gained in wear studies, the device should be equipped to measure the friction occurring between the two cartilage surfaces and the deformation of the cartilages.

3.6 Degenerative Joint Diseases

Degenerative Joint Diseases are characterized by the deterioration and loss of articular cartilage, by the formation of new bone at the margins and the base of the joints, as well as by changes in the composition of the synovial fluid (Sokoloff, Hamermon [85]). Within the framework of this thesis, the interest is focused on osteoarthritis which is the most common form of arthritis. In the very first phase of osteoarthritis, joints are symptom-free. Therefore, specimens are not available for laboratory tests. For this reason, the initial changes in osteoarthritic joints are still unknown and subject to speculation (Meachim, Brooke [86]).

3.6.1 Onset of Osteoarthritis

It is known that in an early stage of osteoarthritis, a lesion in the collagen fiber framework in the articular cartilage can be observed. Freeman and Meachim [87] have suggested that this lesion causes a deterioration of the mechanical strength of the cartilage matrix. Thus, further structural damage can occur during joint use.

Another change that might occur is a change in the proteoglycan synthesis. The proteoglycans give cartilage its special material properties. According to A. Maroudas
[88], protoglycans protect the collagen fibers against damage. Therefore, a change in the synthesis of the proteoglycans might cause fiber damage during joint use.

G. Bently [89] suggests another hypothesis for the onset of osteoarthritis. He believes that enzymes could initiate degradation of cartilage. The collagen fibers as well as the proteoglycans could be attacked by the enzymes released either from the articular chondrocytes or from the articular tissue. The chondrocytes could be stimulated to release enzymes by microstresses. Ehrlich, Mankin et al. [90] continued the work of Bently.

Cartilage damage also could be caused by crystal depositions in the uncalcified zones of cartilage. The crystals would make the cartilage matrix more attackable by mechanical damage. This theory is suggested by S. Y. Ali [91]. In this area, a tremendous amount of work is also done by Dieppe et al. [102].

It is also conceivable that the onset of osteoarthritis can be seen in a pathological disturbance in the tissue remodeling activity at the cartilage-bone interface. This theory is proposed by L. C. Johnson [92].

E. L. Radin [93, 94] considers the problem more from the mechanical side. He states that resilience in the subchondral bone permits the bone to deform under load. Therefore, stress on the cartilage can be reduced by bone deformation. A decrease in bone resilience might be caused by microfractures which were healed by microcallus. Microcallus stiffens the bone.

Finally, another reason for the onset of osteoarthritis can also be a defect in the quantity or quality of the synovial fluid (Furey [103]).

Osteoarthritis is clinically due to a number of different causes. Probably, none of the mentioned causes can be considered separated from the others as the exclusive reason.
3.6.2 Development of the Disease

As mentioned before, in the first phase the disease is symptom-free. In the intermediate stage which follows the first phase, osteoarthritis is characterized by fibrillation, cartilage thinning, and horizontal splitting at the interface between the uncalcified and the calcified zone (Meachim, Brooke [86]). In the beginning, fibrillation is a tangential splitting of cartilage. Later, the splitting goes on vertically along the alignments of the cartilage fiber framework. In the late stage of the disease, a region of calcified tissue is exposed to direct contact with other joint parts.

3.6.3 Symptoms and Signs of Osteoarthritis

The symptoms of osteoarthritis depend on a number of variables. These variables include the duration and severity of changes, the type of the involved joints, and the tolerance of the patient to symptoms. The most important symptoms and signs are pain, stiffness, limitation of joint motion, and joint enlargement (Meachim, Brooke [86]). The occurring pain is usually difficult to localize. In the beginning it appears only with use of the joint; later, the pain bothers the patient at rest too. The stiffness occurs normally after rest, especially in the morning. It rarely exceeds 15 to 30 minutes of duration.
3.6.4 Causes of Osteoarthritis

The cause or the causes for the onset of osteoarthritis are yet not known. Therefore, drugs which can prevent or retard osteoarthritis are not available. Approaches to help osteoarthritic patients include pain relieving drugs, anti-inflammatory drugs, and joint replacement.

Currently, three major categories of theories for the etiology of osteoarthritis exist (Howell [95]). One of them is based on the major role of physical forces and biomaterial failure of articular cartilage. The second attributes a major part of the disease to failing articular chondrocytic responses involving both degradation and repair. The third category considers bony remodeling, synovial responses, microfractures, and vascular changes as primary factors. In this category, cartilage changes are considered as secondary. Figure 10 shows the relationship between the factors of primary interest according to the third category of theories.
Fig. 10. Interrelationship of Bony Remodeling, Synovial Responses, Vascular Changes and Extracartilaginous Factors in the Onset of Osteoarthritis (Howell [95]).
4.0 Materials and Methods

The evaluation of tribological systems in synovial joints might seem to be an important question for the onset and development of degenerative joint diseases. As mentioned before, scientists tend to evaluate the tribological performance of synovial joints by only looking at friction. Our knowledge about the tribological systems in synovial joints, especially about cartilage wear mechanisms, is limited. For the evaluation of a tribological system, it must be taken into consideration that friction, wear, and damage are dependent upon four factors. These are materials, operation conditions, environment, and design. Therefore, besides friction and wear a number of other factors must be taken into consideration for the establishment of the design goals of a test device for cartilage wear studies.
4.1 The Test Device for Cartilage Wear Studies

In Sec. 3.5.6, five cartilage wear studies undertaken by different investigators were discussed in detail. The conclusion of this section was that a new cartilage-on-cartilage test device is needed to undertake wear studies under normal conditions. The new device should offer the possibility of varying the applied load, varying the involved type of motion, influencing the variation of the velocity during each cycle, determining the average value of the sliding speed, controlling environmental data like humidity and temperature, measuring friction, and measuring the deformation of the cartilage. A cartilage test device with the features mentioned above will give the option to carry out tests with healthy cartilage as well as with cartilage from joints in which a degenerative joint disease has already occurred. Therefore, it will be possible to observe changes in friction and wear behavior when degenerative joint diseases appear. The device will also give the opportunity to investigate the effects of different lubricants on the tribological systems in synovial joints. These can be synovial fluids or constituents of synovial fluid (see Table 10). Furthermore, synovial fluid of joints with a degenerative joint disease or artificial fluids can be tested. Experiments with different lubricants and cartilage types may help us to answers questions like whether changes in the wear behavior at the onset of and during a degenerative joint disease, if there are any, are due to changes in the lubrication properties of the fluid or to changes in the material properties of cartilage.

As a side effect, the cartilage test device will also provide researchers with the chance to undertake friction and wear tests with cartilage paired with samples of any other material (e.g., polymers, composites, ceramics).
4.1.1 Development of the Device

The literature search had shown that cartilage wear tests can be conducted either with entire joints or with cartilage specimens. For several reasons (see Table 11) the latter option was chosen for the design of a new test device for cartilage wear studies.

The first, and probably most important, reason is that the purpose of the tests is to investigate the tribological systems under controlled conditions. The great advantage of tests with cartilage specimens can be seen by the fact that the test conditions such as pressure, lubrication, type of motion, variation of the velocity during each cycle, average value of the velocity and environmental conditions are controllable. Therefore, it should be possible to obtain reproducible results. In tests with entire joints, the area of contact as well as the value of the mean pressure would not be measurable. Therefore, the results of tests with entire joints would be uncertain. They must be observed very critically before conclusions can be drawn from them.

The control of the conditions under which tests with entire joints would take place would be difficult. For example, the distribution of the lubricant in the entire joint would not be controllable. It would be very difficult to find out if the lubricant is at the place where it is needed, if it is distributed as in a living joint or if it is gathered in a spot where it has no use. Another problem occurring in connection with the lubrication of a test system of entire joints is a design problem. It would be a problem to keep the lubricant in the joint during the test.

Furthermore, in experiments with entire joints, it would not be possible to determine the exact type of relative motion occurring between the joint surfaces. In most cases, the motion is a mixture of rolling and sliding. In experiments with cartilage specimens, the type of motion is variable and controllable. It is dependent upon the
Table 11. Comparison of Wear Tests with Cartilage Specimens with Wear Tests with Entire Joints.

<table>
<thead>
<tr>
<th>Points of Comparison</th>
<th>Tests with Cartilage Specimens</th>
<th>Tests with Entire Joints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control of test conditions</td>
<td>easier</td>
<td>more difficult</td>
</tr>
<tr>
<td>Lubrication of the test system</td>
<td>easier</td>
<td>more difficult</td>
</tr>
<tr>
<td>Type of motion</td>
<td>controllable, variable</td>
<td>difficult to figure out, fixed</td>
</tr>
<tr>
<td>Velocity</td>
<td>variable</td>
<td>variable</td>
</tr>
<tr>
<td>Actual design of the device</td>
<td>easier</td>
<td>more difficult</td>
</tr>
<tr>
<td>Transfer of results</td>
<td>conceivable</td>
<td>not possible</td>
</tr>
<tr>
<td>General validity of results</td>
<td>considerable</td>
<td>very limited</td>
</tr>
</tbody>
</table>
shape of the cartilage specimens. In general, the shape of the specimens should be chosen so that the type of motion involved would be pure rolling or pure sliding. A mixture of both types can be avoided. That makes it easier to control the tribological conditions in the system. The average sliding velocity can be varied in both cases.

Besides the disadvantages of experiments with entire joints, problems in designing the actual device would occur also, because the motion of natural joints is so complex. The device should be able to simulate the motion of the joint. From the kinematical point of view, this can be difficult, because natural joints often have moving axes of rotation (see Fig. 4). If the simulation of the natural joint motion is not optimal, additional forces will be found in some areas of the cartilage surfaces. Other areas of the joint surfaces perhaps would carry less weight than in natural motion. Even if the device is able to simulate the motion of one joint perfectly, it would be almost impossible to use this device for a variety of joints of the same type, because natural joints always differ slightly from each other.

Results obtained with a device for testing cartilage specimens are much easier to transfer than those found with a device for testing entire joints. Specimens taken from very different types of joints could be examined. It should be possible to transfer the data about the tribological systems gained from the experiments to different cartilage types and make predictions about the wear behavior of different cartilage-on-cartilage systems. The validity of the results of tests with entire joints would be relatively limited. The results would be fixed to one joint type. A device for testing cartilage specimens is much more versatile than a device which employs entire joints.

For the above mentioned reasons the conviction was gained that priority had to be put on cartilage-on-cartilage wear studies with cartilage specimens.

Tests with cartilage specimens can be carried out by bringing two cartilage surfaces together under a defined load, moving them relative to each other, lubricating them,
and determining friction, wear and surface damage. In general, there are three types of relative motion: pure sliding produced by motion on a plane parallel to the surfaces of the test specimens; pure rolling performed by two specimens rolling on each other; and the normal approach. Spinning is basically a special form of sliding. A combination of the types of relative motion is also conceivable. The first option has been chosen for the test device developed in this work. The motion, the mean pressure, and the lubrication of the resulting system will be easily controllable. Therefore, the measurement of friction, wear and deformation will provide acceptable results.

The choice of the shape of the cartilage specimens is tightly linked together with the choice of the type of motion. Furthermore, these two choices have an influence on the question of how the lubricant can be kept in the test area during tests.

### 4.1.2 Design and Features of the Device

The actual cartilage test device is designed and constructed for sliding experiments with two specimens placed on top of each other. The lower specimen is moved relative to the upper one in such a way that a motion of the pure-sliding type is performed. Figure 11 shows a schematic overview of the design of the device. The frame and the x-y table are mounted to a base plate. The frame holds the upper specimen holder, which is allowed to move vertically. The upper specimen holder can neither move horizontally nor rotate. The lower specimen holder sits on the x-y table, which is linked to a kinematic mechanism driven by an electric motor. The kinematic mechanism can be set up in two different ways. It can perform either a linear motion or a circular motion. The motion of the lower specimen relative to the upper one varies with the variation of the kinematic mechanism. The motion of the lower specimen is also either
Fig. 11. Schematic Overview over the Design of the Cartilage-on-Cartilage Test Device for Wear Studies.
linear or circular. For the future, it is planned to equip the device with suitable controls and a computer. This will give the possibility for more complex motions between the cartilages.

The frictional forces occurring during a test between the cartilage specimens are determined by an octagonal ring equipped with a set of strain gages and mounted in the upper specimen holder. The loading forces are determined as well by the strain measurement in the octagonal ring. The vertical motion of the upper specimen is measured by a linear variable displacement transducer (LVDT). The whole system is loaded by an pneumatic cylinder sitting on top of the device.

The design goals of the test device for cartilage wear studies are listed below:

1. To provide the capability of sliding a cartilage specimen (e.g., a cylindrical plug of bone with a layer of cartilage at one end) against another larger specimen (e.g., a larger section of a joint).
2. To mount a variety of cartilage specimens.
3. To provide the capability for keeping the test fluid in the test area and of sampling the fluid after the tests.
4. To measure friction.
5. To measure vertical displacement, e.g., due to deformation and/or wear.
6. To include the capability of varying the applied loads.
7. To include the capability of varying the sliding velocity.
8. To include the capability of varying the type of motion (linear, circular).
9. To provide the capability of controlling the environment (humidity, temperature).

The test device for 'in vitro' cartilage wear experiments should offer the capability of carrying out tests under the following conditions:
Contact geometry : flat-on-flat, convex-on-flat, convex-on-concave
Articular cartilage : swine, but other cartilage types are conceivable
Specimen size : upper specimen: 6 mm diameter,
lower specimen: $\approx$ 15 mm diameter
Applied load : 50 - 100 N
Average pressure : 1.7 - 3.4 MPa
Traverse : > 6 mm
Sliding velocity : 0-20 mm/s
Fluid Temperature : ambient (20 °C) or controlled
Environment : ambient temperature (ca. 20 °C), controlled humidity

These test conditions are about the same which Furey [2] used in his cartilage-on-stainless steel wear experiments.

4.1.2.1 The Upper Specimen Holder

The upper specimen holder is the most complicated part of the whole device because it contains a number of features. Detailed drawings can be found in Appendix A. The specimen itself sits at the lower end of the holder. Therefore, it has to carry the whole amount of the load, which is provided by the air cylinder (23). The specimen is held by two screws (1,2) in a stainless steel shaft (3). One screw (1) prevents the specimen from rotating; the other one gives the specimen a support, so that it cannot slip into (disappear in) the holder. The shaft (3) fits to a piece (5) bearing the octagonal strain ring (6). A pin (4) prevents the shaft (3) from rotating relative to the piece (5).
The octagonal strain ring is mounted to the piece (5) by two screws (7). The octagonal strain ring provided with eight strain gages (8) is used to measure the frictional forces occurring between the cartilage specimens as well as the loading forces. More details about the octagonal strain ring will be given in the next section. On the upper side, the octagonal ring is mounted again to a shaft (9) with two screws (10). The shaft can slide vertically in a case (piece) (11) welded to the frame (12). It is prevented from rotating relative to the case by a pin (13). At the upper end, the shaft is provided with a thread. On the thread a special screw (14) is placed which limits the downwards motion of the shaft. This is a safety precaution for the case in which the cartilage is worn completely away. In this case, the upper specimen holder cannot slide down so far that the lower specimen or something else is destroyed. Furthermore, the whole holder can rest on the screw when the device is not on test, e.g., when the upper specimen is not supported by the lower one. An additional feature is given by a ring-like slider (15), which can be slid over the octagonal ring to protect it against strain when the device is not carrying out tests. The slider protects against tangential stress as well as against stress resulting from rotation of the lower part relative to the upper part with the help of two pins (16). By this feature the strain gages are protected against decalibration by strain. When the device is on test, the slider has to be moved down and fastened by a screw (17) to the lower part of the holder so that the strain gages attached to the octagonal ring can measure the frictional and loading forces which occur. The slider (15) has a slit through which the wires connecting the strain gages with the amplifier are led.

4.1.2.2 The Octagonal Strain Ring

The octagonal strain ring (6) is mounted into the upper specimen holder. It is equipped with eight strain gages to measure the frictional forces resulting from the
sliding motion of the cartilage specimens and the vertical load forces. Thus, the octagonal strain ring is used to observe the frictional behavior of the cartilage on cartilage system as well as to measure the force put on the test system by the loading system.

Figure 12 illustrates the geometry of the octagonal strain ring, the directions in which the forces are acting and where the strain gages are to be mounted. For the determination of the geometric dimensions of the octagon, the strain equations from N. H. Cook and E. Rabinowicz [96] was used.

\[
\varepsilon_{50} = 1.4 \cdot \frac{P_f \cdot r}{E \cdot b \cdot t^2}
\]

\[
\varepsilon_{90} = 0.7 \cdot \frac{F \cdot r}{E \cdot b \cdot t^2}
\]

where

- \( \varepsilon_{50} \) \( \triangleq \) deformation of the octagonal strain ring at \( \Theta = 50^\circ \)
- \( \varepsilon_{90} \) \( \triangleq \) deformation of the octagonal strain ring at \( \Theta = 90^\circ \)
- \( P_f = 10\ldots100 \text{ N} \) \( \triangleq \) frictional force
- \( F = 10\ldots100 \text{ N} \) \( \triangleq \) load applied vertically
- \( r = 8.5 \text{ mm} \) \( \triangleq \) mean radius of the octagon
- \( b = 6 \text{ mm} \) \( \triangleq \) width of the octagon
- \( t = 6 \text{ mm} \) \( \triangleq \) thickness of the octagon
- \( E = 207 \cdot 10^9 \frac{N}{m^2} \) \( \triangleq \) E-Modulus of carbon steel
Fig. 12. Geometry of the Octagonal Strain Ring.

(The numbers 1-8 indicate the strain gages.)
\[ P_f = 10 \text{ N} : \]
\[ \varepsilon_{50} = \frac{1.4 \cdot 10 \text{N} \cdot 8.5 \text{mm}}{207 \cdot 10^9 \frac{\text{N}}{\text{m}^2} \cdot 6 \text{mm} \cdot (6 \text{mm})^2} = 0.53 \cdot 10^{-5} \]

\[ P_f = 100 \text{ N} : \]
\[ \varepsilon_{50} = \frac{1.4 \cdot 100 \text{N} \cdot 8.5 \text{mm}}{207 \cdot 10^9 \frac{\text{N}}{\text{m}^2} \cdot 6 \text{mm} \cdot (6 \text{mm})^2} = 5.3 \cdot 10^{-5} \]

\[ F = 10 \text{ N} : \]
\[ \varepsilon_{90} = \frac{0.7 \cdot 10 \text{N} \cdot 8.5 \text{mm}}{207 \cdot 10^9 \frac{\text{N}}{\text{m}^2} \cdot 6 \text{mm} \cdot (6 \text{mm})^2} = 0.265 \cdot 10^{-5} \]

\[ F = 100 \text{ N} : \]
\[ \varepsilon_{90} = \frac{0.7 \cdot 100 \text{N} \cdot 8.5 \text{mm}}{207 \cdot 10^9 \frac{\text{N}}{\text{m}^2} \cdot 6 \text{mm} \cdot (6 \text{mm})^2} = 2.65 \cdot 10^{-5} \]

The ratio of the difference in voltage \( \Delta V \) resulting from the applied strain to the absolute voltage \( V \) is equal to the strain gage factor \( G \) multiplied by the strain \( \varepsilon \).
\[
\frac{\Delta V}{V} = G \cdot \varepsilon
\]

The signal can be calculated by:

\[
\Delta V = G \cdot \varepsilon \cdot V
\]

where

\[
G = 2.0 \quad \text{gages factor}
\]

\[
V = 12 \text{ V} \quad \text{applied voltage}
\]

\[
P_f = 10 \text{ N} \quad \Delta V_{50} = 2.0 \cdot 0.53 \cdot 10^{-5} \cdot 12V = 0.127 \text{ mV}
\]

\[
P_f = 100 \text{ N} \quad \Delta V_{50} = 2.0 \cdot 5.30 \cdot 10^{-5} \cdot 12V = 1.272 \text{ mV}
\]

\[
F = 10 \text{ N} \quad \Delta V_{90} = 2.0 \cdot 0.265 \cdot 10^{-5} \cdot 12V = 0.064 \text{ mV}
\]

\[
F = 100 \text{ N} \quad \Delta V_{90} = 2.0 \cdot 2.65 \cdot 10^{-5} \cdot 12V = 0.636 \text{ mV}
\]

These calculations are done to determine how large the difference between the voltage outputs of the system is for large and small loads. The occurring voltage differences are important for the sensitivity of the strain gage systems. The selected strain gages provide the opportunity to measure applied forces in the range of at least 10 - 100 N. The sensitivity of the system allows a measurement of differences in the applied
forces of at least 0.5 N. (For more information about the vendor, the type of the selected strain gages, and the calibration, please see the Appendix.)

The deformation of the octagonal under the strain $\varepsilon_{50}$ at $\Theta = 50^\circ$ can be calculated with the following formula:

$$\delta_{p,50} = 9.42 \cdot \frac{P_r \cdot r^3}{E \cdot b \cdot t^3}$$

$$\delta_{p,50} = 9.42 \cdot \frac{100N \cdot (8.5\text{mm})^3}{207 \cdot 10^9 \frac{N}{m^2} \cdot 6\text{mm} \cdot (6\text{mm})^3}$$

$$\delta_{p,50} = 8.62 \cdot 10^{-3}\text{mm}$$

$$\delta_{p,50} = 0.34 \cdot 10^{-3}\text{inches}$$

The deformation of the octagonal under the strain $\varepsilon_{90}$ at $\Theta = 90^\circ$ can be calculated with the following formula:

$$\delta_{p,90} = 1.79 \cdot \frac{F \cdot r^3}{E \cdot b \cdot t^3}$$

$$\delta_{p,90} = 1.79 \cdot \frac{100N \cdot (8.5\text{mm})^3}{207 \cdot 10^9 \frac{N}{m^2} \cdot 6\text{mm} \cdot (6\text{mm})^3}$$
\[ \delta_{p,90} = 1.64 \cdot 10^{-3} \text{mm} \]

\[ \delta_{p,90} = 0.064 \cdot 10^{-3} \text{inches} \]

The deformation is in both cases so small that no plastic deformation will remain after the reapplication of the 100 N force.

The strain gages are wired as shown in Fig. 13. Each set of strain gages is connected to a bridge amplifier. The signals from the amplifier are sent to a recorder where they are put on paper or tape.

### 4.1.2.3 The Lower Specimen Holder

The lower specimen holder consists basically of two parts. For detailed drawings, please see Appendix A. The specimen sits in a circular piece (18). It is held by four special screws (19). This design allows the testing of specimens of different shapes and sizes. The piece bearing the specimen rests on a base plate (20) which is mounted to the top of the x-y table (22). The base plate is provided with a circular depression in which the upper piece (18) fits exactly. Therefore, the specimen cannot slide across the x-y table. Two pins (21) sitting in the depression of the base plate (20) fit into little holes in the bottom side of the holder (18). They prevent the specimen from rotating on the base plate.
Fig. 13. Schematic of the Strain Gage Bridges.

(The numbers 1-8 indicate the strain gages. The strain gages 1-4 measure the vertically applied force, the strain gages 5-8 measure the frictional force.)
4.1.2.4 *The Loading System*

A single-acting pneumatic cylinder (23) is used to load the test system. The cylinder has a 3/4-inch bore and a 1-inch stroke. It is linked to a gas pressure bottle with controllable pressure by an 1/8-inch NPT connection. The cylinder is mounted with special mounting hardware (25) and a stand (26) to the frame (12) of the device. The applied load is variable. A maximum pressure of 10 bar can be applied to the pneumatic cylinder. The cylinder acts directly on the center of the shaft (9) of the upper specimen holder. The value of the applied load is observed by the strain measurements in the octagonal ring (6) mounted into the upper specimen holder. For more details about the measurement of the load, see Section 4.1.3.2.

4.1.2.5 *The X-Y Table*

A free-floating 12 x 12 inch x-y table supports the lower specimen holder. It is composed of two single axis positioning tables mounted on top of each other with their sliding ways perpendicular to each other. The x-y table can perform every conceivable motion in the x-y plane. Its maximum travel distance per axis is equal to seven inches. The weight of each positioning table is 75 N. The load capacity is equal to 930 N. That means, that the whole x-y table can carry over 855 N. The applied load is carried by preloaded linear ball bearings comprised of hardened and ground stainless steel bearing balls and ways.

The x-y table is mounted directly to the bottom plate of the device by four 1/4-inch screws. It is driven by an fractional-hp electric motor with the option of variation of the speed. The motion of the x-y table, and therefore the relative motion between the
cartilage specimens, is either linear or circular depending upon the kinematic mechanism connecting the table with the motor. For more information about the vendors and the types of the x-y table or the electric motor, please see the Appendix.

4.1.2.6 The Mechanical Drive of the X-Y Table

The motion performed by the x-y table depends upon the mechanical connection between the x-y table and the driving motor. The kinematic mechanism is easily variable. Only a few parts need to be changed. Therefore, it provides the user of the device with two different options of the motion between the specimens: a) linear motion, b) circular motion. Both motion options can be used for different test series. Figure 14 illustrates the kinematic mechanisms used for the realization of the motion options. The driving speed of the electric motor is variable. Thus, the sliding speed between the cartilage specimens is variable, too. The motor is provided with a power of a fractional hp. For power calculations, please see the Appendix. The velocity variations are discussed in detail in Sec. 4.4.

4.1.2.7 The Linear Variable Displacement Transducer (LVDT)

The linear variable displacement transducer (LVDT) measures the vertical displacement of the upper specimen. This feature determines the displacement during a test, but is also gives the opportunity to compare the positions of the upper specimen before and after the tests. The difference between these two positions can be due to cartilage wear or to deformation of the cartilage resulting from the applied load. It will be possible to gain information about the amount of wear as well as about the defor-
Fig. 14. Kinematic Mechanism
   a) for Linear Motion
   b) for Circular Motion
mation in connection with data gained from the analysis of the specimens themselves (see Section 4.2.3). A differentiation between displacement due to wear and displacement due to deformation will be possible. This will be discussed later.

The LVDT is connected with the upper specimen holder by a plate (31) and it is also attached to the frame (12) of the device. For more information about the vendor and the type of the LVDT, please see the Appendix. The calibration of the LVDT must be undertaken before each test. It can be done by turning the calibration screw of the LVDT holder. This screw allows one to bring the LVDT to its zero position.

4.2 Cartilage Specimens

4.2.1 The Geometry of the Cartilage Specimens

The geometry of the upper specimen is fixed. The shape and size of the lower specimen can vary in shape and size as long a certain size is not exceeded. The cross section of the upper specimen has to be circular to fit into the specimen holder. Its diameter is \( d = 6 \text{ mm} \). The length should not be greater than \( l = 30 \text{ mm} \). The upper specimen is allowed to be shorter than 30 mm. Figure 15 illustrates the geometry of the upper specimen.

The cartilage surfaces of the specimens will never be perfectly flat. For the avoidance of edge effects, the surface of the upper specimen should preferably be convex. The surface of the lower specimen should preferably be concave or flat, because this shape makes it easier to keep the lubricating fluid in the test area.
Fig. 15. Geometry of the Upper Specimen.
The lower specimen is allowed to have different shapes. The cross-section of this specimen can be circular, rectangular, or it can have any other shape as long as its size does not exceed the inner diameter of the lower specimen holder \( d = 50 \text{mm} \). The minimum extension of the cartilage surface in one direction should be twice the size of the diameter \( d \) of the upper specimen. The bottom surface of the lower specimen should be parallel to the cartilage surface, if possible. The height of the lower specimen should be at most \( h = 20 \text{mm} \). If a specimen is not at least 10 mm high, thin plates need to be placed on the bottom of the specimen holder before the specimen is mounted. If the cartilage surface of a specimen is not parallel to its bottom surface, wedge-shaped plates can be put between the specimen and the bottom plate of the holder, so that the cartilage surface becomes parallel to the x-y plane of the x-y table. The selection of this geometry of the specimens was made in close connection with the selection of the type of relative motion between the specimens (see Chapter 4.2).

### 4.2.2 The Selection of Joints for Cutting Specimens

Within the framework of this thesis for the selection of usable joints for cutting specimens for the experiments, the author focused on the pig joints because these could be obtained from the Department of Animal Science on campus.

For the avoidance of unexpected side effects, it would be an advantage to use in one test cartilages taken from surfaces facing each other in normal joint use. As mentioned in Sec. 4.2.1, the surfaces of the upper specimen should preferably be convex and the surfaces of the lower specimen should preferably be concave. The curvature of the cartilage surfaces should be small. Larger joints have normally the advantage that the radius of the curvature of the cartilage surfaces is larger. Furthermore, the cartilage
surfaces must have a sufficient size, especially for cutting the lower specimen. Therefore, two suitable joints can be selected from the pig for cutting specimens:

1) the shoulder joint in the forelimb

2) the stifle joint in the hind limb

Figures 16 and 17 illustrate the skeleton of a right forelimb and the skeleton of a left hind limb of a pig, respectively. The size of the cartilage surfaces in these two joints is sufficient for cutting.

The shoulder is the juncture between the scapula and the humerus in the forelimb of the pig. The shoulder is a ball and socket joint in which sliding predominates (Nickel, Schummer, Seiferle [97]). The joint surface of the scapula is concave. The joint surface of the humerus is convex. Therefore, the lower specimen should be cut out of the scapula and the upper specimen out of the humerus. Figure 18 shows a picture taken of the neck of the scapula with its cartilage surface. The ruler in the picture indicates that the size of the cartilage surface is sufficient to cut the lower specimen with a minimum diameter of 15 mm. Figure 19 shows the cartilage surface of the head of the humerus. The picture illustrates that this cartilage surface also has a sufficient size to cut the upper specimen with a diameter of 6 mm out of it.

The stifle joint in the hind limb is composed of three bones—the femur, the tibia, and the patella. These three bones form basically two joints, one between the femur and the patella and the other one between the femur and the tibia. Therefore, the stifle joint of the pig offers two possibilities to take specimens from surfaces facing each other in normal joint use. First, the specimens can be taken from the femur and from the patella; and second, they can be taken from the femur and from the tibia. Figures 20, 21, and 22 show pictures of the cartilage surfaces of the patella, the tibia, and the femur.
Fig. 16. Skeleton of the Right Forelimb of a Pig, Medial Aspect (Sack [98]).

A - Scapula, B - Humerus, C - Radius, D - Ulna, E - Carpal bones, 
F - Metacarpal bones, G - Phalanges.
Fig. 17. Skeleton of the Left Hind Limb of a Pig, Medial Aspect (Sack [98]).

A - Femur, B - Patella, C - Tibia, D - Fibula, E - Tarsal bones, F - Metatarsal bones, G - Phalanges.
Fig. 18. Picture of the Cartilage Surface of the Neck of the Left Scapula of a Pig.
Fig. 19. Picture of the Cartilage Surface of the Left Humerus of a Pig.
Fig. 20. Picture of the Cartilage Surface of the Patella of a Pig.
respectively. The type of motion occurring in the joint between the femur the patella is predominantly sliding. The motion between the femur and the tibia is a mixture of rolling and sliding (Nickel, Schummer, Seiferle [97]). In both cases the cartilage for the upper specimen should be taken from the femur because its shape is convex. The size of the cartilage surface of the femur is sufficient for cutting the upper specimen (see Fig. 22). The cartilage for the lower specimen should be taken from the patella or from the tibia. The cartilage surface of the patella can be classified as concave. The cartilage surface of the tibia is concave and convex, but it is possible to cut specimens out of it with a minimum diameter of 15 mm. The curvature of these specimens will still allow one to undertake experiments.

In the beginning, a number of other joints were taken into consideration for cutting specimens. The selection of the two mentioned joints was made because the size of the cartilage surface in these joints is larger than in the other joints. Therefore, the specimens taken from these joints will offer the largest flexibility for the variation of the type of motion involved. On the other hand, some of the cartilage surfaces of the carpal bones as well as of the tarsal bones also have a sufficient size to cut specimens out of them. Because the size of the cartilage surfaces of these bones is smaller, the area from which the specimen should be cut cannot be selected.

The hip joint of the pig is a ball and socket joint. Although the ball has a sufficient size, the joint is not usable for specimens. The socket of this joint is not a complete socket. It is formed like a ring and supports the ball only with a relatively small surface (see Fig. 23).

4.2.3 The Test Preparation of the Cartilage Specimens
Fig. 21. Picture of the Cartilage Surface of the Left Tibia of a Pig.
Fig. 22. Drawing of the Right Femur of a Pig (Getty [99]).
Fig. 23. Left Hip Joint of a Pig.
Fig. 24. Steps of the Specimen Cutting Technique Proposed and Used by H. Lipshitz and M. J. Glimcher [84] (drawings taken from M. J. Furey [100]).

a) Placement of the cutting tool perpendicular to the cartilage surface
b) Cutting of the thin cartilage layer
c) Cutting of the plug
d) Final trim
e) Removal of the plug.
For the preparation of test specimens, H. Lipshitz and M. J. Glimcher [84] proposed a special technique. They designed a holder which allows a controlled cutting process of specimens from sections of the patella portion of the distal end of adult bovine femora. The cartilage surface of specimens which are cut with this technique is both flat and perpendicular to the cylindrical shaft of the underlying bone. Using this method, H. Lipshitz and M. J. Glimcher have cut specimens with a diameter of \( d = 5.7 \) mm which had an acceptable flat surface. The technique pays special attention to the margins of the specimens. The cutting process is divided into several steps (see Fig. 24). First, the cutting tool is put into a position perpendicular to the surface. In the second step, only the thin cartilage layer is cut. Then the underlying bone is cut with a tool which is a little bit bigger than the first one. In this way the margins of the specimens are not exposed to special effects such as overheating during the cutting process. In a fourth step the plugs get their final trim. The last step is the removal of the plug. The specimens for the cartilage on cartilage test device should be cut in a similar way. This was the method and system used by M. J. Furey for his study of cartilage wear at The Children's Hospital Medical Center in Boston [100].

The cutting process of the lower specimen is easier, because the geometrical shape of the lower specimen is variable. It can be circular as well as rectangular. Therefore, it can be cut out of the bone by linear cuts. Furthermore, the condition of the margins of the specimens is not that important. Edge effects initiated by the margins will not appear, because the margins of the lower specimens would not be included in the test area.

Before and after the cutting process, the bone samples and the prepared specimens should be stored at a temperature of about \(-20^\circ C\). This will guarantee that the changes in the cartilage after the slaughtering of the animal will be kept small. Low temperatures minimize the bacterial degradation of the cartilage. It is also conceivable to use

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inhibitors killing the bacteria in the storage room. But the influence of the inhibitors on the cartilage is not known. As soon as the cartilage specimens are taken out of the refrigerator, the humidity of their environment should be controlled and fixed at a high level. In first phase of doing experiments, the environmental temperature during the tests could be the ambient temperature which is close to 20°C.

4.2.4 The Determination of Cartilage Wear and Damage

The planned cartilage-on-cartilage tests will give information about the friction and wear behavior of the test system. The determination of the friction is done by the measurement of the frictional forces by the octagonal strain ring (see Section 4.1.3.2). The determination of cartilage wear is more difficult and complex. Two different analysis methods (visual and chemical) should be used to gain a compete picture of the wear behavior. First, the surfaces of the specimens can be examined with a scanning electron microscope (SEM) after the tests. As mentioned before, this involves a long and tedious procedure. One of the possible techniques for the scanning electron microscopy of articular cartilage is already described in Sec. 3.1. Second, after a test the hydroxyproline content of the lubricant as well as of the solid wear debris can be measured to determine the exact amount of wear of the cartilage specimens. Since the content of the hydroxyproline is constant throughout the whole cartilage layer, it can be used to measure the extent of wear of articular cartilage. The technique for this analysis was described in detail by H. Lipshitz, R. Etheredge III and M. J. Gümcher [82]. The analysis of the hydroxyproline content in the lubricant and the wear debris as a possibility for measuring wear was first mentioned in Sec. 3.5.6.
For the analysis of the tests by the method described by Lipshitz, Glimcher, and Etheredge III, the whole test fluid as well as all wear debris must be saved and analyzed after the tests. Therefore, the cartilage specimens must be rinsed with a fluid which has no chemical impact on the test fluid or the cartilage.

A disadvantage of this test analysis is that it is impossible to distinguish between the wear of the upper cartilage specimen and the wear of the lower specimen. But there is the opportunity to estimate approximately the difference between the two amounts of wear from the two specimens by observation with the scanning electron microscope.

4.3 Relative Motion between the Specimens

As mentioned before, the test device for cartilage wear tests is designed for sliding experiments. The device gives two options for the type of relative motion. The lower specimen is mounted to an x-y table. The table is mounted to a kinematical mechanism which is driven by an electric motor. The x-y table performs a motion depending upon the kinematical mechanism between the table and the motor. The device gives two motion options (see Fig. 14, Section 4.1.3.6). First, the lower specimen moves back and forth on a straight line and performs therefore, a linear motion (a). Second, the lower specimen moves on a circular pathway (b). The two options for motion between the specimens given by the device are shown in Fig. 25.

The fact that the motion on a circular pathway is continuous must be considered as an advantage in comparison to the back and forth motion on a straight line. In the mode of linear motion, the velocity drops to zero at every reversal. At least in the regimes of hydrodynamic and elasto-hydrodynamic lubrication this must be considered
Fig. 25. Two Basic Forms of Relative Motion between Two Specimens
a) Linear Motion
b) Circular Motion

-----Lower Specimen
———Upper Specimen
as a disadvantage, because the lubricating fluid film breaks when the velocity drops to zero. Therefore, the fluid film needs to be built up two times per cycle. In addition, at every reversal of the linear motion, the cartilage layer of the upper specimen moves relative to its underlying bone as indicated in Fig. 26. The impact of this effect on the test results is not known. The velocity profiles of both types of motion are different. They are discussed in Sec. 4.4.

For both types of relative motion (a and b) shown in Fig. 27, the x-axes and the y-axes of the upper and lower specimen must be kept parallel to each other. If they would rotate relatively to each other, a spinning motion would be performed. Therefore the relative velocity between the specimens would be different at every place of the cartilage surfaces. This would complicate the analysis of the experiments.

The test device provides the possibility to adjust the travel distance $a$ to the shape and size of the lower specimen. For both types of motion, the travel distance $a$ should be at least equal to the diameter $d$ of the upper specimen. In this way the cartilage specimens travel from one extreme point to the other at least so far that the upper specimen covers an entirely fresh area of the lower specimen. The choice of the travel distance greater or equal to the diameter $d$ has two advantages. First, every spot of the test area of the surface of the lower specimens is exposed to approximately the same amount of contact. If the travel distance is less than the diameter $d$, a certain spot in the middle of the test area would be exposed to contact to a larger extent than the rest of the test area. Second, the lubricant gets a chance to lubricate the whole test area freshly once during each cycle. The test area of a specimen is the cartilage area which should be observed and analyzed after the tests.

The test area of the upper specimen includes the whole cartilage surface of the specimen. The test area of the lower specimen is indicated in Fig. 27. Its extent depends upon the travel distance $a$. The test area of a specimen which is tested with
Fig. 26. Effect on the Upper Specimen at the Reversal Point of the Linear Motion (Furey [1]).
Fig. 27. Test Areas of the Lower Specimen
   a) Linear Motion
   b) Circular Motion
linear motion can be divided into two different sections as indicated in Fig. 27. The exposure of these sections to contact is different.

4.4 Sliding Velocity

The test device offers the possibility to vary the sliding velocity. The driving motor is variable in speed. The sliding velocity can be adjusted to the type and shape of the chosen cartilage specimens. In the case of linear motion, the velocity varies harmonically in the form of a pure sine curve. Figure 14 (Section 4.1.3.6) shows the geometrical arrangement of the driving mechanism. Figure 28 shows the schematic illustrations of the mechanical arrangements for linear and circular motion. The distance \( x \) in Fig. 28 a) is dependent upon the angle \( \phi \).

\[
x = l + r \cdot \cos \phi
\]

Therefore, the sliding velocity \( v \) is dependent upon the angular velocity \( \dot{\phi} \).

\[
v = r \cdot \sin \phi
\]

The velocity is also dependent of the value of the radius \( r \). At the reversal points of the linear motion, the sliding velocity becomes always zero. This could have an impact on the lubrication of the test system, because any hydrodynamic film would not exist at the reversal points.

In the case of motion on a circular pathway the velocity is constant. Therefore, tests can be run at different constant sliding velocities. The results of these tests will show if the sliding velocity has an impact on the tribological processes in the test sys-
Fig. 28. Schematic Illustration of the Kinematic Mechanism

a) for Linear Motion
b) for Circular Motion
tems and of which type this impact would be. Figure 29 shows the time-velocity behavior for each type of motion.

4.5 The Lubrication of Cartilage Test Specimens

The travel distance of the specimens relative to each other is chosen so that the upper specimen gets into contact with an entirely new area of the lower specimen once a cycle (see Fig. 24). Therefore, the lubricant gets the chance to lubricate the whole area of the lower specimen during each cycle. Different fluids can act as lubricants. It is planned to undertake experiments with the fluids used by Furey [2] (see Table 10). Furthermore, wear tests can be conducted using healthy synovial fluids and synovial fluids taken from osteoarthritic joints.

During a test, the lubricant is needed between the two surfaces. Therefore, it is kept from flowing away by a thin and sharp metallic ring pressed into the cartilage surface of the lower specimen (see Fig. 30). Attached to the equipment of the device, a number of such rings with different diameters can be found. Thus, for different specimen sizes and different travel distances, fitting rings can be selected. The size of the ring must be chosen so that it allows enough space for the sliding motion. But, it should not be too large because more synovial fluid would be required to lubricate the system. The metallic ring should be pressed 1-2 mm deep into the cartilage layer.
Fig. 29. **Variation of Sliding Velocity during Tests**

a) Linear Motion, $v = r \cdot \sin \phi$

b) Circular Motion, $v = \text{constant}$
Fig. 30. Schematic Illustration of the Lower Cartilage Specimen with a Metallic Ring Pressed in the Surface to Contain the Test Fluid.
4.6 Experimental Procedure

Before an experiment can be started, the strain gages must have been calibrated. More about the calibration of the strain gages can be found in the Appendix. The cartilage specimens must be cut. The steps to be taken to cut the specimens are described in Sec. 4.2.3. The following steps must be carried out for cartilage wear experiments:

1. Prepare the kinematic mechanism so that the x-y table performs the desired motion.
2. Clamp the specimens in the holders.
3. Press the metallic ring into the surface of the lower specimen.
4. Place the holders in the device.
5. Switch on the recorders connected with the strain gages.
6. Switch on the recorder connected with the LVDT.
7. Calibrate the LVDT by moving the screw for calibration.
8. Put the test fluid on the lower specimen in the metallic ring.
9. Load the system by activating the pneumatic cylinder carefully.
10. Start the electric motor.
11. Set a timer and the cycle counter.
12. Permit necessary time for the experiment.
13. Measure the temperature and the humidity of the environmental air at regular intervals during the test.
14. Close the pressure bottle connected to the pneumatic cylinder and release the pressure from the cylinder.
15. Stop the electric motor.
16. Switch off the recorders connected with the strain gages.
17. Switch off the recorder connected with the LVDT.
18. Remove the specimen holders including the specimens from the device.
19. Collect the lubricant and rinse the specimens in order to gather the wear debris.
20. Freeze the lubricant samples and rinses.
21. Freeze the cartilage specimens.
22. Examine the LVDT record.
23. Examine the strain gage record presenting the behavior of the frictional forces.
24. Examine the strain gage record presenting the behavior of the loading forces.
25. Analyze the temperature and humidity values taken during the test.
26. Observe the specimens with a SEM.
27. Analyze the lubricant samples and the rinses for their hydroxyproline content.

* The temperature of the environment should be kept at about 25°C. The humidity should show a constant value during the tests, which should be as high as possible. This will prevent the cartilage surfaces from drying out.

4.7 The Analysis of Cartilage Wear Rate

As mentioned in Section 4.4.3, the test specimens should be analyzed in two ways in order to get information about the wear which occurred during a test. First, the specimens should be observed with a SEM. In this way, the surface structures and damage can be studied. Second, the hydroxyproline content in the lubricant and in the

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wear debris should be determined after the test. This gives information about the amount of wear which occurred during the test. The second analysis technique does not give any information about the place where the wear occurred, neither on which specimen nor on which spots of the specimens. Therefore, the analysis of the wear rate would be incomplete without using the first technique. The wear rate is the mass or volume of material removed per time unit from the sliding surfaces. M. J. Furey [3] found in his experiments with cartilage on stainless steel that the wear rate for these systems lubricated with different fluids was constant over a six-hour period (see Fig. 31). For the experiments with the test device designed within the framework of this thesis, the wear rate is also expected to be constant. For the investigation of the wear rate, during a wear test fluid samples should taken at various times. Then, the analysis of the hydroxyproline content can give information about the wear rate over the time. The amount of wear will also depend on the applied load. How this dependence will look like is not yet known.

The record gained with the LVDT will also give some information about the wear rate. But the LVDT records will say nothing about where the wear occurs. An LVDT record shows the amount of vertical motion with the time. The LVDT can measure a displacement of the upper specimen holder due to cartilage wear and/or deformation. The deformation could be elastic or plastic and it can occur in either one or both specimens. In elastic deformation, the applied stress and the strain initiated are linearly related. Elastic deformation disappears as soon as the stress is removed. In plastic deformation, the applied stress results in a permanent deformation (Halling [20]). It is known that cartilage generally behaves elastically (Kempson [101]).

Figure 32 illustrates four basic possibilities of how an LVDT record could look like. At the moment when the load is applied, elastic deformation occurs. When the system is unloaded the elastic deformation disappears. If neither wear nor plastic deformation
Fig. 31. Wear Rate of Cartilage on Stainless Steel Found by M. J. Furey [3].
occurred, the position of the upper specimen relative to the frame before and after the test is the same. A difference between the position before and after the experiment results from wear, from plastic deformation, or from both effects. It is unlikely, that under the test conditions given in Sec. 4.1.3 plastic deformation will occur. Therefore, displacement curves of type a and c can be expected.
Fig. 32. Displacement of the Upper Specimen Holder Relative to the Frame
a) no wear, no plastic deformation.
b) plastic deformation only
    c) wear only
    d) wear and plastic deformation
5.0 Conclusions

The literature search undertaken provided the author with an overview of the research carried out in the field of biotribological processes in synovial joints. As a result, the author found that very little work has been done on cartilage wear. Five studies of cartilage wear were found. Three of these wear studies include wear tests which were carried out under exaggerated conditions. In one case, the investigators applied tremendous loads to the system. In the second case, the experiments were run “dry”, which means unlubricated, and in the third case, cartilage was abraded with a rotating steel abrader. The result of the third mentioned test can hardly give any information about the tribological processes in synovial joints. The exaggeration of test conditions might cause changes in the wear mechanisms in the biological systems. It might be almost impossible to discover such changes because the investigators have no references for comparison. Therefore, tests under exaggerated conditions must be considered very critically. Furey [2, 3] and Swann and Radin [49] undertook wear tests under conditions close to conditions which occur in living joints. Both test devices used in these studies offered no or limited opportunities for the variation of test parameters, e.g., type of
motion, applied load, velocity, variation of the velocity during each cycle, type of specimens, and the fluid composition. Therefore, within the framework of this thesis, a cartilage test device for wear studies was designed and built which offers the opportunity to vary all above mentioned parameters. Furthermore, friction, wear, and deformation of cartilage can be measured with this device.
6.0 Future Plans and Recommendations

The test device for cartilage wear studies is designed and constructed in such a way that it is possible to expand its capacity and features in the future. At the moment, the device is equipped with only one pair of specimen holders. Therefore, only one test can be undertaken at a time. But, the x-y table and the frame of the device offer enough space and capacity to carry four pairs of specimen holders. This gives the possibility to undertake four experiments at a time, thus saving time and improving on statistical analysis of the data. The test device could be used with a reference fluid R and a test fluid A at the same time as indicated in Fig. 33. Figure 33 shows a top view of the test device for cartilage wear studies. Each circle indicates one test unit.

Before the device is used for a large series of experiments, a box made of plexiglass should be designed in which the whole device is placed. This box could be isolated against the environment, thus making it easier to control the temperature and humidity.

Another future development can be concerned with the drive and control of the x-y table. The device will be provided with a number of additional features when the free-floating x-y table is equipped with lead screws and stepper motors. These can be
Fig. 33. Test Device for Cartilage Wear Studies Used with a Reference Fluid R and a Test Fluid A at the Same Time.
linked to a control unit and personal computer. Depending upon the software and the input parameters of the computer, the device will give an infinite number of options for the type of motion performed by the motor driven x-y table. Furthermore, the variation of sliding velocities during each cycle can be achieved and influenced in a number of different ways. The velocity can be held constant or it can follow a certain mathematical curve. It will be possible to have delay times between motion sequences as well as to create continuous motion. Linear motion is an exception. Such motion will never be continuous, since the velocity will drop to zero at the reversal points.

The cartilage test device offers a large variety for developments and extensions in the future.
7.0 References


<table>
<thead>
<tr>
<th>No.</th>
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Appendix A. Drawings of the Cartilage Test Device

All dimensions given in the drawings are in inches.
BILL OF MATERIALS

1. Screw
2. Screw
3. Upper Specimen Holder
4. Screw
5. Holder
6. Octagonal Strain Ring
7. Screw (2)
8. Strain Gages
9. Shaft
10. Screw (2)
11. Case
12. Frame
13. Pin
14. Nut
15. Slider
16. Key
17. Screw
18. Lower Specimen Holder
19. Screw (4)
20. Plate
21. Pins (2)
22. X-Y Table
23. Single-Acting Pneumatic Cylinder
24. Mounting Hardware
25. Stand
26. Screw (4)
27. Screw for the Calibration of the LVDT
28. Screw (2)
29. Holder
30. LVDT
31. Plate
32. Holder
33. Screw (2)
34. Screw (2)
35. Connector for the X-Y Table for Linear Motion
36. Connector for the X-Y Table for Circular Motion
37. Screw
38. Linear Slider
39. Connector
40. Case
41. Pin
42. Linear Bearing
43. Screw (4)
44. Screw (4)
45. Holder for the Linear Bearing
46. Disc
47. Shaft
48. Nut
49. Key
50. Disc
51. Belt
52. Snap Ring
53. Angular Contact Ball Bearing
54. Holder
55. Screw (6)
56. Electrical Motor
Fig. 34. Assembly Drawing of the Upper Specimen Holder Including the Octagonal Strain Ring.
Fig. 35. Upper Specimen Holder (Part 3, Material: Stainless Steel).
Fig. 36. Holder (Part 5, Material: Carbon Steel).
Fig. 37. Octagonal Strain Ring (Part 6, Material: Carbon Steel).
Fig. 38. Shaft (Part 9, Material: Carbon Steel).
Fig. 39. Case (Part 11, Material: Carbon Steel).
Fig. 40. Frame (Part 12, Top View, Material: Carbon Steel).
Fig. 41. Frame (Part 12, Side View, Material: Carbon Steel).
Fig. 42. Nut (Part 14, Material: Carbon Steel).
Fig. 43. Slider (Part 15, Material: Carbon Steel).
Fig. 44. Lower Specimen Holder (Part 18, Material: Stainless Steel).
Fig. 45. Base Plate of the Lower Specimen Holder (Part 20, Material: Aluminum).
Fig. 46. Assembly Drawing of the Loading System and the LVDT.
Fig. 47. Stand (Part 25, Material: Carbon Steel).
Fig. 48. Calibration Screw for the LVDT (Part 27, Material: Bronze).
Fig. 49.  Holder (Part 29, Material: Carbon Steel).
Fig. 50. Plate (Part 31, Material: Bronze).
Fig. 51. Holder (Part 31, Material: Carbon Steel).
Fig. 52. Assembly Drawing of the Driving Mechanism.
Fig. 53. Top View Driving Mechanism.
Fig. 54. Connector for the X-Y Table for Linear Motion (Part 35, Material: Carbon Steel).
Fig. 55. Connector for the X-Y Table for Circular Motion (Part 36, Material: Carbon Steel).

Appendix A. Drawings of the Cartilage Test Device
Fig. 56. Linear Sliding Shaft (Part 38, Material: Carbon Steel).
Fig. 57. Connector (Part 39, Material: Carbon Steel).
Fig. 58. Case (Part 40, Material: Nylon).
Fig. 59. Pin (Part 41, Material: Carbon Steel).
Fig. 60. Holder for the Linear Bearing (Part 45, Material: Aluminum).
Fig. 61. Disc (Part 46, Material: Carbon Steel).
Fig. 62. Shaft (Part 47, Material: Carbon Steel).
Fig. 63. Holder (Part 54, Material: Aluminum).
Appendix B. List of Purchased Items
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<tr>
<th>Item</th>
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<th>Type</th>
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<td>Linear Bearing Pillow Block</td>
<td>Dixie Bearings</td>
<td>SPB-6</td>
</tr>
<tr>
<td>Ball Bearing Angular Contact Type</td>
<td>Dixie Bearings</td>
<td>SKF 7205 DY</td>
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<tr>
<td>Snap Ring</td>
<td>Dixie Bearings</td>
<td>5000/206</td>
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<tr>
<td>LVDT</td>
<td>SCHAEVITZ</td>
<td>250 MHR</td>
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<tr>
<td>Strain Gages</td>
<td>MM</td>
<td>CEA-06-015UW-120</td>
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<tr>
<td>X-Y Table</td>
<td>DAEDAL</td>
<td>3000 Series</td>
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</tbody>
</table>
Appendix C. Calibration of the Strain Gages
The calibration of the strain gages mounted to the octagonal strain ring is a small project in itself. First, the calibration of the normal force response and the calibration of the tangential force response must be done separately. Then, the calibrated system must be tested when both forces act simultaneously. Normally, for the readings of the normal and for the tangential force, there is very little crossover. Therefore, the normal and the tangential force can be detected independently.

Both calibrations can be done by applying defined loads to the octagonal strain ring. At the same time, the output voltage due to the applied force must be measured. In this way, the relationship between the change in voltage to the applied load can be figured out.
Appendix D. Calculation of the Power Required for the Electric Motor
The relative motion between the two cartilage surfaces is initiated by the rotation of a disc to which a pivot is attached decentered. The disc is driven by the electric motor. The force is applied to the pivot. The maximum distance \( r \) between the center of the disc and the center of the pivot is 15 mm. The moment against which the motor has to act is

\[
M = F \cdot r
\]

where

\[
\begin{align*}
M & \triangleq \text{moment} \\
F & \triangleq \text{force} \\
r & \triangleq \text{radius}
\end{align*}
\]

The force \( F \) is equal to the frictional force between the cartilage specimens. The potential forces occurring due to the curvature of the cartilage specimens are very small and therefore negligible. The frictional force will not exceed 400 N. This value occurs when \( 4 \times 100 \text{ N} \) are applied to the cartilage test systems and a coefficient of friction of \( \mu = 1.0 \) is taken into consideration.

\[
\mu = \frac{F}{N}
\]

\[
F = \mu \cdot N = 1.0 \cdot 400 = 400 \text{N}
\]

In this case, the moment equals

\[
M = F \cdot r = 400 \cdot 0.15 = 6 \text{Nm}
\]
The power required can be calculated with

\[ P = M \cdot \omega \]

where

\[ \begin{align*}
P & \triangleq \text{power} \\
\omega & \triangleq \text{angular velocity}
\end{align*} \]

It is planned to undertake experiments at

\[ \omega = 40 \, \frac{\text{rev.}}{\text{min.}}, \]

therefore,

\[ P = 6 \cdot 40 \, \frac{\text{rev.}}{\text{min.}} = 6 \cdot \frac{2}{3} \, \frac{\text{Nm}}{\text{s}} = 4 \text{W} \]

When a safety factor \( s = 2 \) is taken into account, the actual required power is equal

\[ P_a = P \cdot s = 4 \cdot 2 = 8 \text{W} \]

\[ P_a = 12.2 \cdot 10^{-3} \text{hp} \]

Therefore, an electric motor with the power of \( 1/50 \) hp is sufficient.
Bettina Burkhardt was born on June 7th of 1962 in Hannover in northern Germany. She grew up in a little town near Hannover and finished High School in 1981. Two years later she received the Bachelor Degree in Mechanical Engineering from the technical university “Carolo Wilhelmina Universitaet zu Braunschweig” in West Germany. Then she specialized in the field of “Verfahrenstechnik” (thermal and mechanical separation processes). In August of 1987, the same university awarded her the German Master’s Degree in Mechanical Engineering. Her thesis was about the separation behavior of fluid-solid mixtures in hydrocyclones. In September of 1987, she came to Virginia Polytechnic Institute and State University in an international student exchange program. She enrolled in the Master of Science program in Mechanical Engineering and completed all degree requirements in December of 1988.