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A Novel Method for Calculating the Frictional Properties of Articular Cartilage Using a Material Testing Machine

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1. Introduction

1.1 Osteoarthritis

Osteoarthritis (OA) is a normal degenerative joint disease which causes joint destruction, chronic pain, depression, disability, and social in patients. It is considered to be a widespread condition affecting the elderly where 60–90% of over 75 year olds are affected (Hinton, Moody et al. 2002).

OA is often a disabling and progressive disease resulting from different risk factors, including age, genetics, trauma, overuse, gender, obesity as well as an imbalance of physiologic processes. With OA, however, joint degeneration is characterized by the bone, synovium, and the cartilage changes which leads to pain and disability (Fig.1) (Slemenda 1992). Obviously OA is a long pathophysiological process, and in this pathophysiological mechanisms the synovium, cartilage, and bone are all involved (Fig.2). Current research in OA biomarkers, pathogenesis, treatment and tirbology has broadened immensely in recent years, because of the contribution of all three joint compartments to disease progression.

In the very beginning, such as the knee, OA can be characterized by the gradual loss of articular cartilage (AC) within synovial joints. The biochemical changes in cartilage are characterized by the following: possible changes in the size of collagen fibril ,reduced proteoglycan (PG) concentration and aggregation of PG, increased rate of synthesis and increased water content and degradation of matrix macromolecules (Borthakur, Mellon et al. 2006).

In the most extreme cases, the AC may be worn off totally, because of bone-on-bone surface rubbing. There are no current treatments proven to restore cartilage or cure the disease processes. For this reason, studies on early changes in the processes of human OA are very important (Abramson and Krasnokutsky 2006).

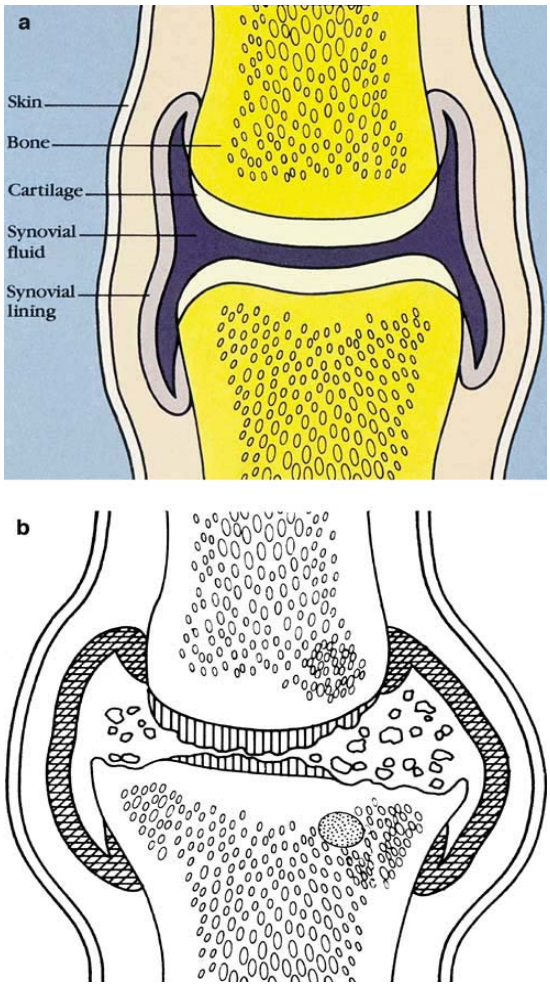


Fig.1: Schematic picture of the normal (a) and end-stage osteoarthritic (b) joint. OA is accompanied by loss of the AC, thickening of synovium, the generation of wear particles, and capsule disturbances in the subchondral bone. (Krasnokutsky, Samuels et al. 2007).

But OA is more than a disease of cartilage, because the synovitis can also occur in early OA and can be subclinical. Arthroscopic studies suggest that the synovium shows localized proliferative and inflammatory changes in 50% of OA patients many of whom do not appear to have active inflammation (Fig.3) (Krasnokutsky, Samuels et al. 2007).

The synovium produces some of the metalloproteinases and chemokines that degrade cartilage. The cartilage itself can also produce some destructive molecules in a vicious autocrine and paracrine fashion. In turn, products of cartilage breakdown, resulting from enzymatic destruction or mechanical, can stimulate the release of collagenase and other hydrolytic enzymes from synovial cells and lead to vascular hyperplasia in OA synovial membranes (Pelletier, Martel-Pelletier et al. 2001). Some researchers (Abramson, Attur et al. 2006) demonstrate that the osteophytes and thickening of subchondral bone are also characteristic of OA, by using imaging studies and pathology specimens clearly (Fig. 4).

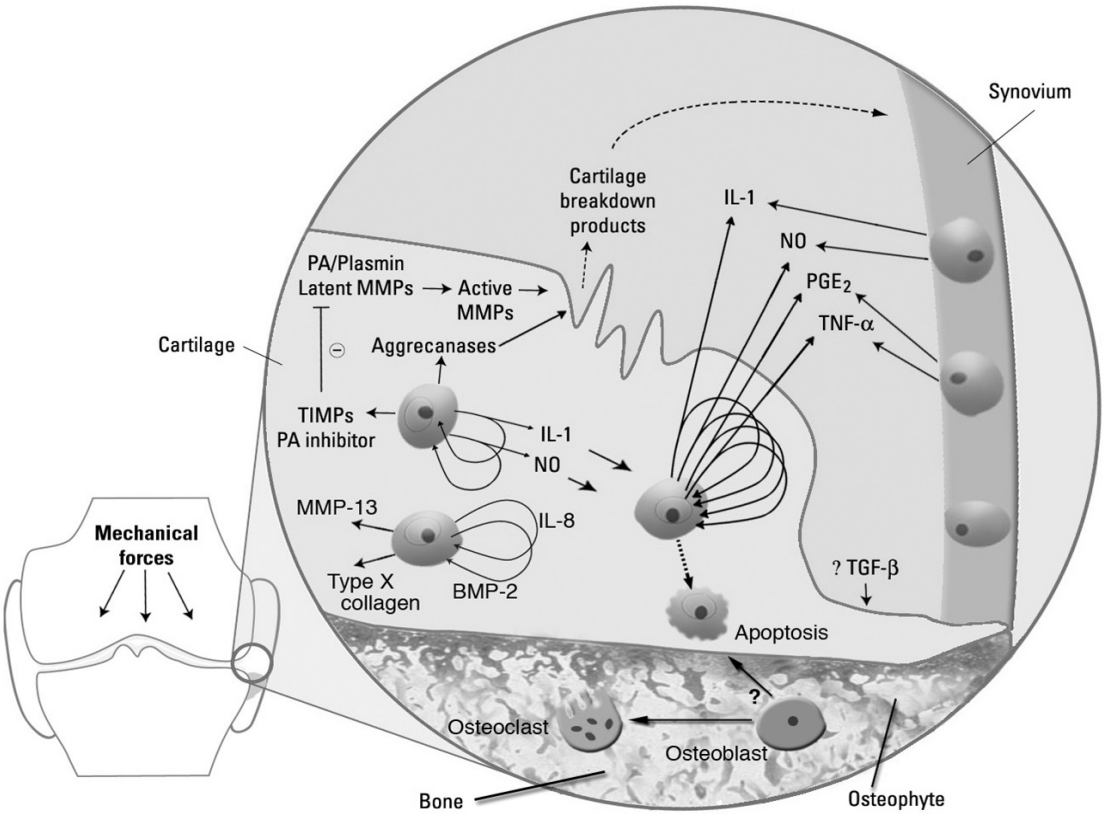


Fig.2: Schematic drawing of molecular pathogenesis of osteoarthritis. (Abramson, Attur et al. 2006) .

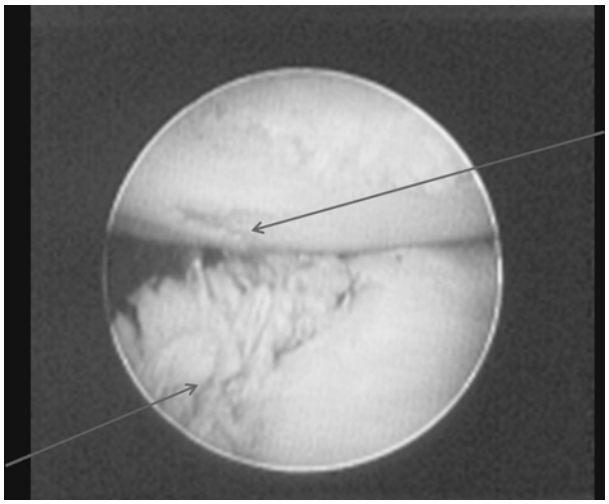


Fig.3: Synovitis and cartilage damage seen on knee arthroscopy (Ayral, Pickering et al. 2005).

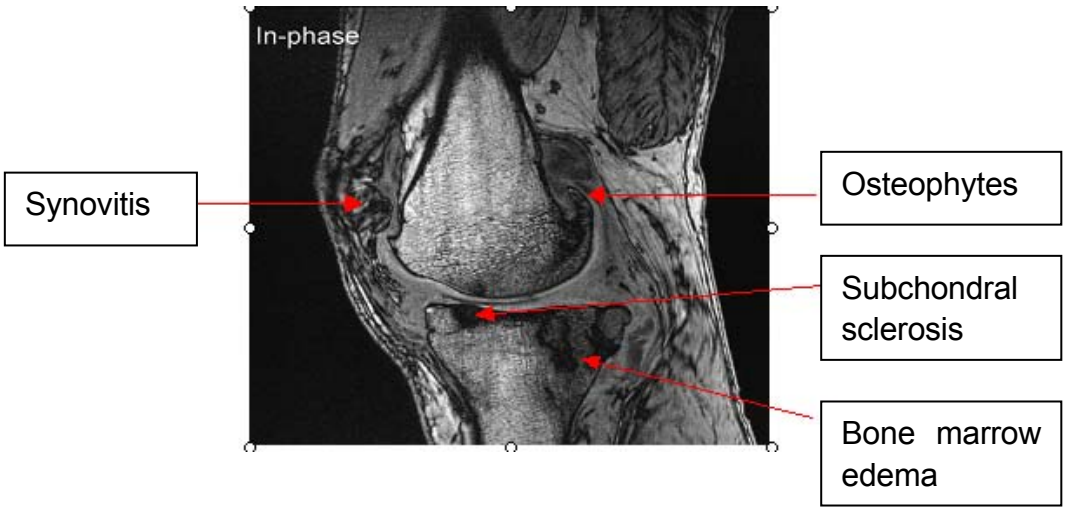


Fig.4: MRI image showing subchondral sclerosis,osteophytes, synovitis and bone marrow edema in an osteoarthritic knee (Ayral, Pickering et al. 2005) .

1.2 Articular Cartilage

There are three primary functions of articular cartilage: to distribute and support forces generated during joint loading, to guide and stabilize joint motions and to contribute to joint lubrication (Ayral, Dougados et al. 1996). Articular cartilage also provides lubrication and a smooth surface, to permit the movement of opposing surfaces with minimal friction and wear (Mow, Gibbs et al. 1989). Joint cartilage has a very limited capacity for repair after injury which is the intrinsic nature of cartilage, because it is a tissue type that is poorly supplied by the lymphatic system, blood vessels, and nerves. Many clinical conditions, including but not limited to arthritis, trauma and congenital or acquired joint diseases, lead to a loss of cartilage tissue in human joints. In summary articulate cartilage provides little scope for its natural self-repair (Campbell 1969), (Fuller and Ghadially 1972), (Mankin 1982).

Articular cartilage consists of collagens, water, cells, proteoglycans, and other matrix biomolecules, and it is a highly organized structure. Articular cartilage is kind of a viscoelastic substance(Fig. 5) (Potter, Jawetz et al. 2007).

On a tissue and molecular scale, hyaline articular cartilage consists of superficial, transitional, and radial zones (Potter, Jawetz et al. 2007). The superficial zone is the thinnest zone, which is subdivided into 2 layers: an acellular surface and a deep zone consisting of chondrocytes. These chondrocytes express proteins with lubricating and protective functions (Roth and Mow 1980), (Woo and Buckwalter 1988). The transitional zone consists of different oriented collagen fibers which give this zone great strength and tensile stiffness and may resist shear forces generated during use of the joint. Theses fibers help to distribute stress more uniformly across loaded tissue. The major part composed of collagen type II 4 in the radial zone, the chondrocytes and collagen fibrils are oriented in columns

perpendicular to the articular surface (Bullough and Goodfellow 1968). Because of the special structure, articular cartilage has resilience to compression, while transmitting and distributing load, thereby reducing peak stresses on underlying subchondral bone.

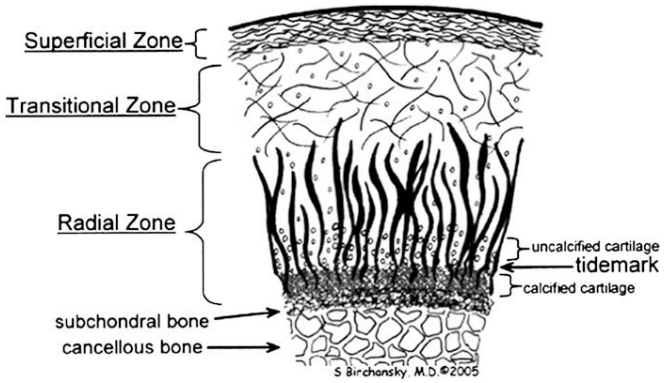


Fig.5: Schematic drawing of cartilage zonal histology (Potter, Jawetz et al. 2007) .

The cartilage has traditionally received the most attention in the study of OA because of the gross damage found in imaging studies and pathology, and the multitude of biochemical processes that are activated.

1.3 Tribology

Tribology covers all the fields of lubrication, friction and wear. It is a word that was first used in 1966 in report of Jost. It's definition is as followed: tribology is the science and technology of interacting surfaces in relative motion and of the practices related thereto (Hori and Kato 2008).

Functional biotribology mainly studies friction, wear and lubrication. Functional biotribology is a useful way to better understand how and why cartilage becomes osteoarthritis. Functional biotribology emphasizes surface characteristics and properties in the joint and at the mean while lubricant substances can reduce friction and wear of interacting surfaces. Some lubrication has been studied in several experiments and are accepted to be exploit to reduce the coefficient of friction in cartilage-on-glass (Swann, Hendren et al. 1981),(Gleghorn, Jones et al. 2009), rubber-on-glass (Jay 1992) and cartilage-on-cartilage (Schmidt, Gastelum et al. 2007) test systems.

Synovial joints of the human body consist of articular cartilage, bone, menisci, ligaments, and synovium. They are complex living biological and mechanical systems that allow for joint articulation and movement with minimal friction and wear.

As living materials, synovial joints are far more complex than those found using all kinds of engineering materials. In the human body's joints, friction, wear, and lubrication are important phenomena that are general in diverse biological joints, and low friction is necessary for the synovial joints.

1.4 Research of tribology

Many researchers have studied the friction of articular cartilage (AC) using a variety of methods, especially with the tribology way. The basic structure of a tribological system is shown in Fig. 6. It consists of body, counter body, interfacial medium, and surrounding environment. For a natural joint the two cartilage surfaces are the two bodies in contact, the synovial fluid is the interfacial medium, and the surrounding environment is defined by the human body milieu.

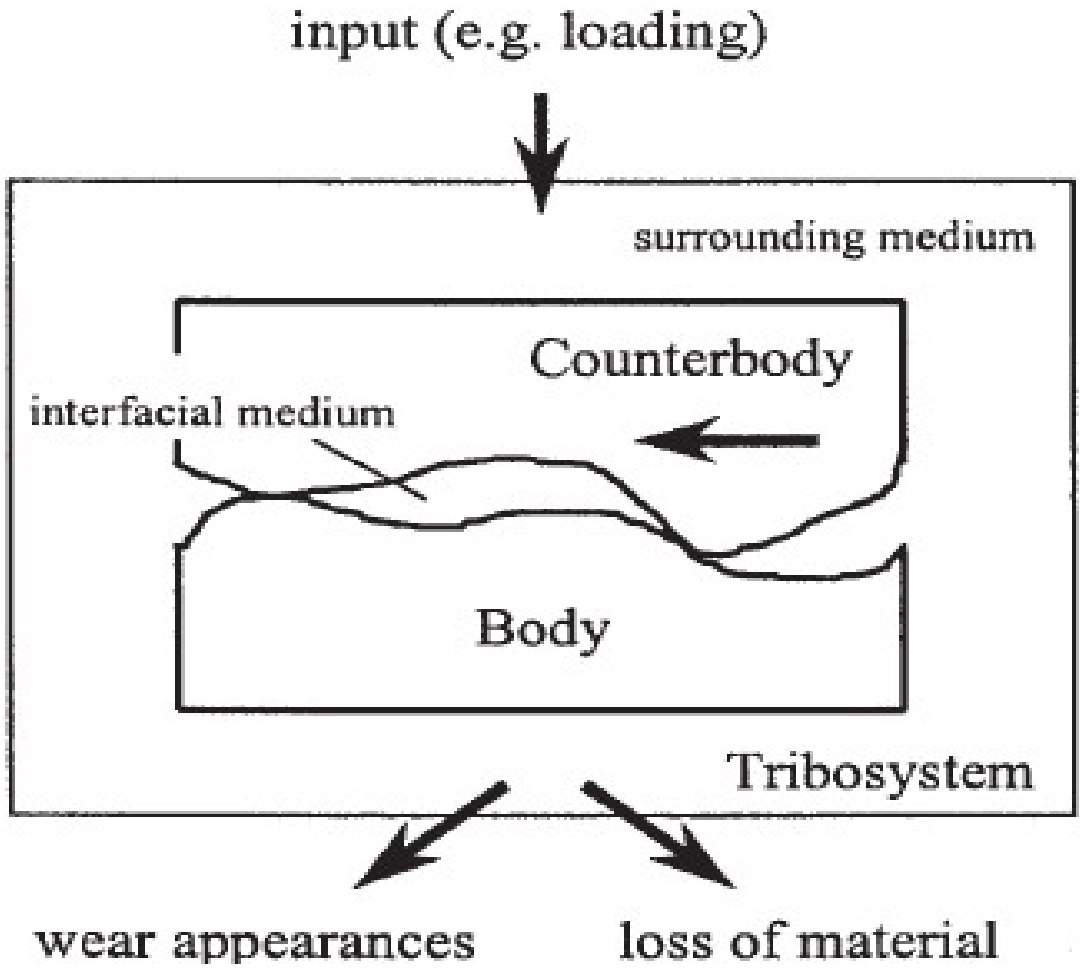


Fig.6: Basic structure of a tribological system (Wimmer, Grad et al. 2004).

Pendulum system had also been used to study the properties of the synovial joints. Drewniak (Drewniak, Jay et al. 2009) examined two analysis methods for

calculating the coefficient of friction(μ) using a simple pendulum system and BL6 murine knee joints as the fulcrum. They used a stanton linear decay model and an exponential model to estimate the decaying pendulum oscillations.

They drew a conclusion that the exponential model was a better way to estimate the experimental data for predicting the frictional properties of intact joints in pendulum systems (Fig.7).

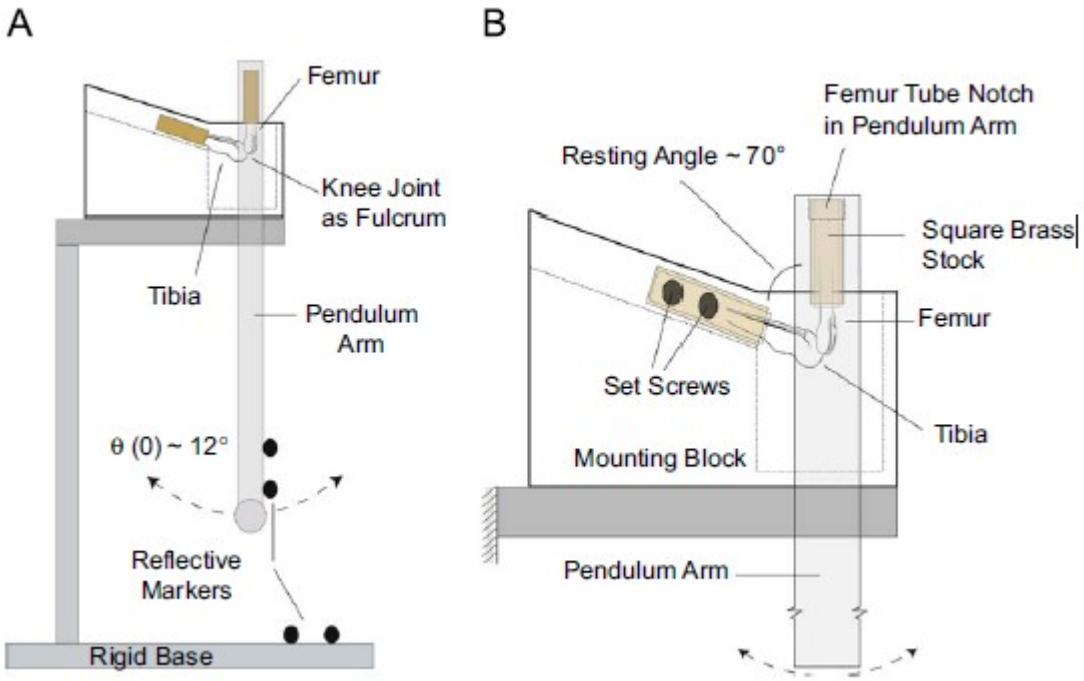


Fig.7: Schematic drawing of simple pendulum system used for amplitude decay data collection.

As the pictures shows that the tibia is mounted to a base platform and the pendulum arm is fixed to the end of the femur. The arm is set to an initial angle of 12°, and allowed to oscillate freely until damping out completely (Gleghorn, Jones et al. 2009).

Gregory D. Jay et al. (Jay, Torres et al. 2007)studied the association between friction and wear in synovial joints with pendulum systems (Fig. 8). Technique of whole the pendulum apparatus using mouse knee joints in which the joint capsule left intact and muscles were removed.

The tibia is fixed at an initial angle 45° and when the femur is kept perpendicula the knee joint angle is 135°. To simulating the weight of an adult mouse standing on limb, 20g weight is used to load on the joint. The fulcrum of the pendulum located

at the knee joint. The femur is manually moved from the perpendicular by 30° and allowed to oscillate freely at the knee joint until joint motion stops.

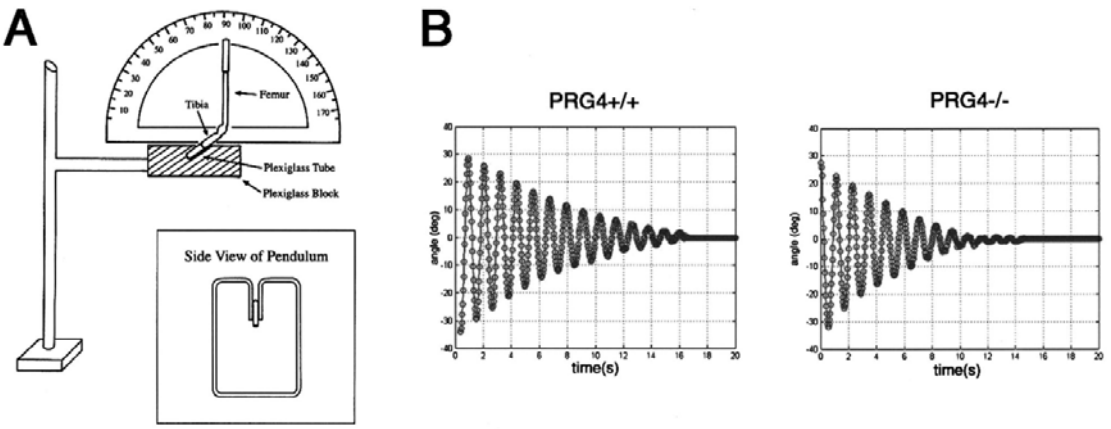


Fig.8: Schema of the pendulum apparatus used to measure whole joint coefficient of friction (μ), and representative data (Jay, Torres et al. 2007) .

In this study, through the image processing analysis frictional coefficient (μ) was calculated by measuring deceleration of the pendulum (a=dv/dt). The result exhibits that friction is coupled with wear at the cartilage surface in vivo. They also suggest that acquired lubricin degradation occurring in inflammatory joint diseases which predisposes the cartilage to damage. Lastly, they also imply hat lubricin, or similar biomolecules, will have applications in man-made devices in which reducing friction is essential.

While there are some benefits with a pendulum system, there are also some disadvantages with a pendulum system, like pendulum weight, range of motion, resting angle, frictional force and data analysis. This model also neglects aerodynamic drag which is created by the pendulum apparatus.

Mechanisms of osteoarthritis progression may be explained by the comparison of deformations from healthy knees and degenerated. Knowledge of deformation shapes in whole joints in vitro would be beneficial to the design and evaluation of repaired cartilage (Butler, Goldstein et al. 2000),(Guilak, Butler et al. 2001), and it also would be advantageous in the development and validation of mathematical models of intact joints. On the other hand, as a step toward in vivo measurements, the characterization of joint cartilage deformation in whole joints in vitro is necessary.

In another study (Jay, Elsaid et al. 2004), Jay and coworkers displayed the increases in the coefficient of friction in synovial fluid joints collected from patients

with knee joint synovitis following injury. Anyway, whether lubricin can simply be injected or it should be induced and/or enhanced by some growth factors, it will be a matter for more future research.

In a short, many tribological systems have been undertaken to investigate its underlying principles for tissue engineering and related cartilage research. In a recent review, (Neu, Komvopoulos et al. 2008) relate concepts of basic biochemistry, mechanics, and molecular and cellular biology to biotribology of natural and tissue engineered biomaterials.

1.5 Friction of synovial joints

The law of friction between two solid surfaces was studied by Amonton, and its empirical law was established by the year 1800. The friction force is the resistance when a body slides against another body, and arises in the direction directly opposite to the direction of moving.

From Amonton`s law, the coefficient of friction is defined as the following formula:

$$F = \mu W$$

F is the friction force, W is the external normal load, and μ is the frictional coefficient.

Amonton`s equation relates F to W through the coefficient of friction. There are two kinds of friction force: 1) the static frictional force, and 2) the dynamic frictional force. The static friction force is defined as the force required initiating relative movement to the normal force between the surfaces. The dynamic friction coefficient is defined as the friction force to the normal force when the two surfaces are moving relative to each other.

Of cause, this formula was defined from the simple friction model, like moving a small block on a surface of a table. Well in living synovial joints it is far more complicated than the simple mode. There are full of synovila fluid in joints, which generally reduce friction and wear of interacting surfaces. Further more there is not only slid friction exists in the living joint but also rolling friction.

In order to measure the friction coefficient, one surface is brought into contact with another and moved relative to it (Fig.9). When the two surfaces contact, the perpendicular force is defined as the normal force N. Normally in a simple friction model the static and dynamic friction coefficients are not very hard to measure. But in a living dynamic joint, when the joint surface is sliding over each other, surface

interaction occurs through isolated microscopic contacts, the contact area will also change. So in a living joint the value of friction coefficient is not static but dynamic.

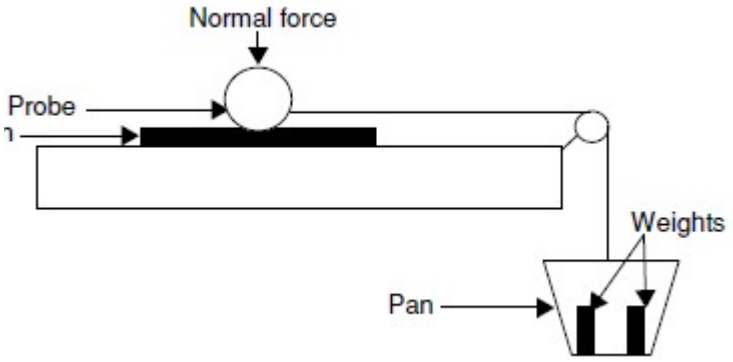


Fig .9: Schematic apparatus system used by Comaish, S (Comaish and Bottoms 1971).

On the other hand, due to the continued loading of the tissue and the following loss of fluid load support, in living joints the coefficient of friction shows a time-dependent response (Fig. 10).

A time dependent coefficient of friction response is normally studied with cartilage surfaces sliding against different solid surfaces, which have usually been attributed to interstitial fluid pressurization of the hydrated tissue (Krishnan, Caligaris et al. 2004).

Another property of cartilage is time-depended elasticity which called viscoelasticity. Previous research has separated cartilage viscoelasticity into flow-dependent and flow-independent regime (Fortin, Soulhat et al. 2000). They describe the time-depended elasticity property with a fibril-reinforced biphasic model. These results demonstrate the biomechanical properties of the articular cartilage.

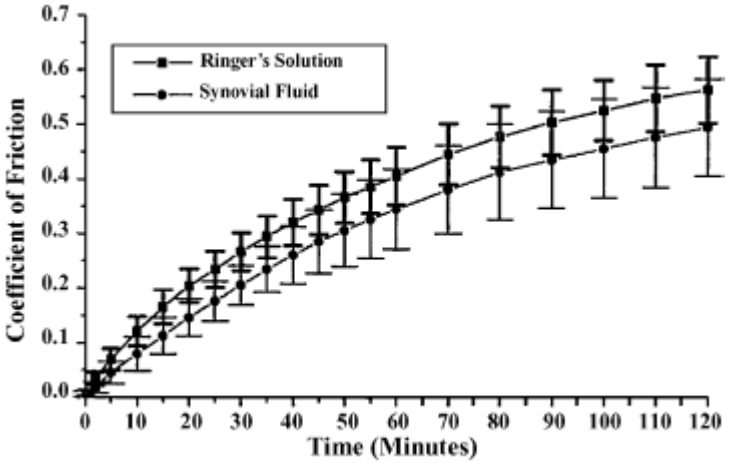


Fig.10: Coefficient of friction (mean (n=9) ±SD) of articular cartilage measured in a plug-against-metal model. Counter face model in Ringer's solution and synovial fluid lubrication (Forster and Fisher 1999).

1.6 Wear of synovial joints

In human being, wear may result in excruciating pain during joint movement following cartilage degradation in osteoarthritis.

Comparatively, fewer studies have been devoted to explain the origins and evolution of cartilage wear. In pure mechanical terms, wear is defined as the loss of material from the contact surfaces due to mechanical action between them.

In addition to the mechanical wear, frictional heating produced from surface rubbing could also enhance the biochemical and/or biomechanical degradation of biological tissues, and cartilage tissue specially.

Wear mechanisms include adhesion, fatigue, abrasion, cavitation, impact, erosion, and corrosion. In the case of cartilage tissue, a loss of PGS or alterations in the collagen network, etc. may be the mean mechanical problems. Wear of cartilage tissue may be exacerbated due to a loss of factors including, but not limited to, trauma, abnormal biomechanical loading, and loss of lubrication mechanisms, etc. Anther contribution of degeneration of wear is altered mechano-chemical properties cause by, metabolic disorders, proteolytic enzymes, and pathological changes in the collagen-proteoglycan matrix. These factors may be acting alone or together to increase the articular cartilage wear rates(Burrage and Brinckerhoff 2007) , (Rowan and Young 2007), (Cawston and Wilson 2006).

Simon (Simon 1971) studied the wear of cartilage by measuring the weight of the accumulated debris and the depth of wear against a metal brader. Synovial fluid

was demonstrated to have properties which protected cartilage from wear that were lost when digested with trypsin. More recently, researchers used an articulating cartilage against cartilage configuration and lubricant analysis for measuring the wear cartilage in vitro. They made a conclusion that, increased loads lead to increased wear of native articular cartilage (Lipshitz, Etheredge et al. 1975),(Katta, Stapleton et al. 2008).

1.7 Lubrication of articular cartilage

Articular joints in the human body show wonderful wear resistance and lubrication. Cartilage surfaces in synovial fluid support pressures up to ~200 atmosphere (Morrell, Hodge et al. 2005). When two cartilage surfaces slide on each other the friction coefficients is in the range 0.0005–0.04 (Forster and Fisher 1996), and usually do not show signs of wear over the entire life of a healthy person.

Under living joint conditions, adsorption of the lubricant to the bearing surfaces can minimize the friction and wear between two cartilage surfaces, because it can prevent direct contact between the two surfaces. So lubricant normally reduces friction and wear of interacting surfaces.

Synovial fluid, and its components like hyaluronic acid (HA), glycoproteins (GAGS) which is the mainly lubricin and surface active phospholipids all have been proved to be the lubricants of boundary lubrication in synovial joints. The major function of lubricants is to provide an easily sheared film between surfaces in relative movement.

Lubrication of traditional engineering bearings can be achieved through the application of lubricious films. Generally these lubricious films consist of natural or synthetic substances that are often blended with special additives. The properties of these lubricious films is that they can either physically adsorb at the surfaces (physisorption) or chemically react with the surfaces (chemisorption) to form and replenish low-friction (Norris, Stabile et al. 2008), (Neu, Komvopoulos et al. 2008).

Mucin proteins, recently, have received a host of attention in recent years due to their role as biological lubricants in different tissues, such as saliva, respiratory tract, and synovial fluid (Cardenas, Elofsson et al. 2007), (Carraway, Perez et al. 2002),(Radin, Swann et al. 1970), (Stonebraker, Wagner et al. 2004). These proteins show the abilities of effecting lubrication and, in turn, surfacing tissue protection against mechanical wears.

1.7.1 Synovial fluid

Synovial fluid is a dialysate of blood plasma without the haemoglobin, or clotting factors (fibrinogen). The important components of synovial fluid are high molecular weight hyaluronate, which is responsible for its viscosity. Synovial fluid is responsible for reducing the friction levels during joint articulation (Jay, Haberstroh et al. 1998).

In earlier vitro studies by Simon (Simon 1971) and Lipshitz (Lipshitz, Etheredge et al. 1975) et al. all the results have shown that when compared to saline lubrication, the synovial fluid lubrication can drastically reduce the wear of cartilage pins articulating against metal surfaces.

Forster and Fisher (Forster and Fisher 1999) study the synovial fluid lubrication using an in vitro cartilage pin against metal plate articulation model. The result corroborates that the synovial fluid lubrication can reduce the coefficient of friction between the articulating cartilage surfaces when compared to Ringers solution lubrication under boundary lubrication conditions.

More recently, Schmidt et al (Schmidt, Gastelum et al. 2007), (Schmidt, Gastelum et al. 2007), (Schmidt and Sah 2007) showed the boundary lubrication ability of synovial fluid in an in vitro disk-on-annulus setup. In these studies, synovial fluid was shown to provide lower friction levels compared to PBS under boundary lubrication conditions in a cartilage rotating against cartilage model.

1.7.2 Hyaluronic acid (HA)

Evidence has been presented, that hyaluronic acid is a boundary lubricant in joints in support of and against the effectiveness. Hyaluronic acid is the load bearing component of synovial fluid. This strongest evidence was presented by Radin (Radin, Swann et al. 1970), who separated hyaluronate from synovial fluid using centrifugation techniques. The research of hyaluronic acid showed that the active load bearing component was in the proteinacious layer rather than the hyaluronate layer. In contrast, many recent in vitro studies have established the utility of hyaluronic acid in joint lubrication (Fig. 11) (Forsey, Fisher et al. 2006),(Bell, Ingham et al. 2006).

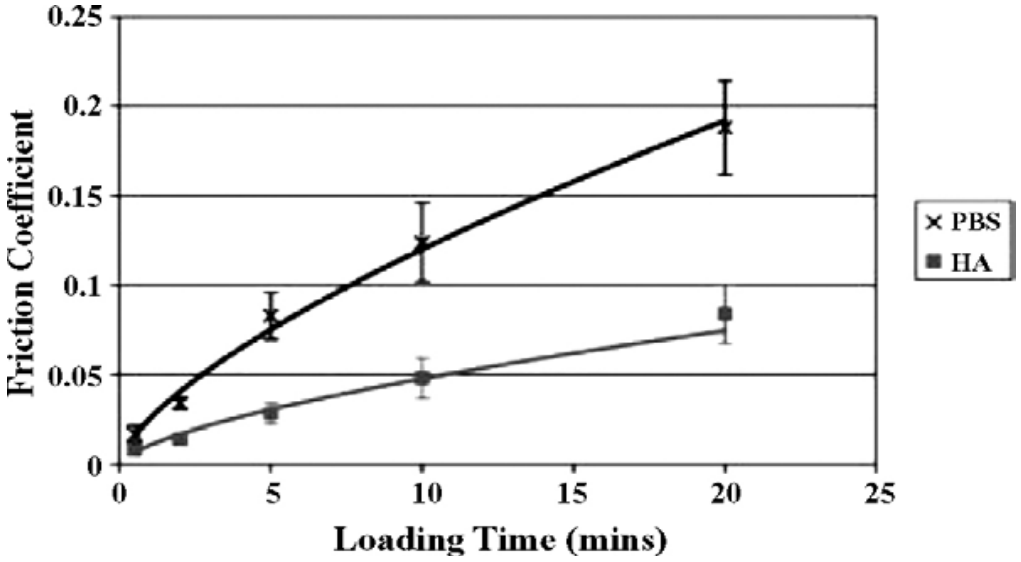


Fig.11: Frictional coefficients for native articular cartilage under static loading conditions in PBS and HA lubricants (Bell, Ingham et al. 2006).

HA was also shown the abilities to penetrate the articular cartilage surface, and concentrate itself around the lacunae of chondrocytes indicating potential beneficial biochemical effects, while providing lower startup coefficient of friction levels compared to Ringers solution under boundary lubrication conditions for human osteoarthritic cartilage (Bell, Ingham et al. 2006). There is no evidence yet to support the usefulness of HA in conditions where there is extensive damage to the cartilage tissue.

1.7.3 Lubricin

Lubricin, a component of synovial fluid and a mucinous glycoprotein was identified in the early 80s as a potential boundary lubricant by Swann (Swann, Silver et al. 1985) and further characterization was carried out by Jay (Jay 1992) .

The gene Prg4 has been identified as the regulator for both lubricin and another protein called superficial zone protein (SZP) found on the surface of articular cartilage (Schumacher, Hughes et al. 1999).

Lubricin is produced by both synoviocytes lining the joint capsule, and the superficial zone chondrocytes in articular cartilage. Unlike hyaluronic acid, most of the studies of lubricin are still limited to in vitro and animal models and the utility of lubricin in joint lubrication in a clinical setting is yet to be investigated.

This research will mainly focus on the biotribology of articular cartilage, and aim to build a novel in vitro experimental model, that can be applied to study fundamentals of cartilage friction, wear and lubrication. We hope such new

tribological models systems hold a distinct advantage to understand cartilage natural behavior, degradation processes, and evaluate various cartilage treatment therapies.

2 Materials and Methods

2.1 Animals

Five female sheep's wrist joint (1.0-1.6 kg) were obtained from the animal factory, they were fed a standard diet and had water ad libitum. All animal care, housing, and treatment were performed according to the German animal welfare act. Specimens were stored at -20 ℃ for1–2weeks (Fig. 12).

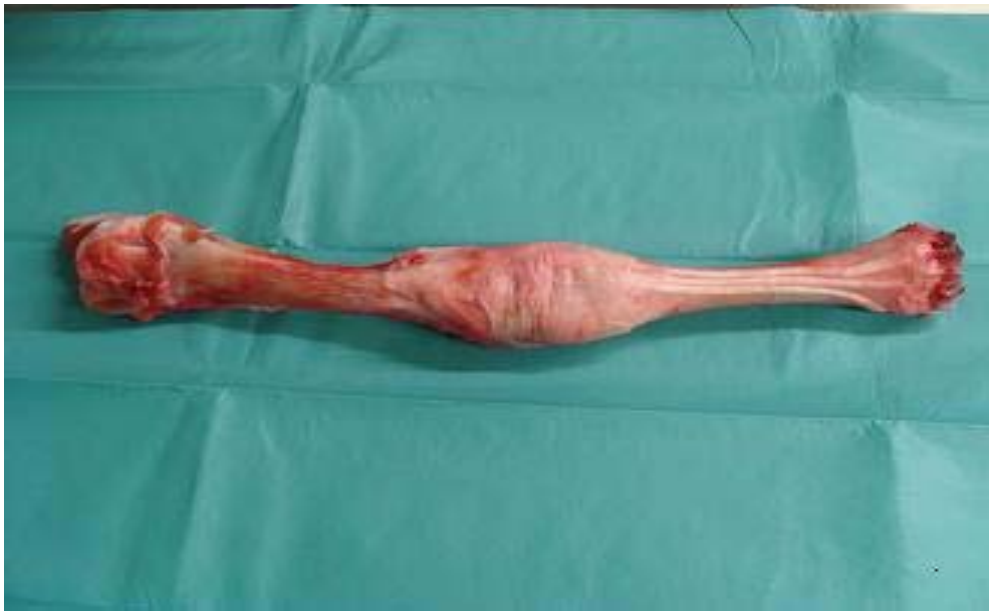


Fig.12: Picture of prepared specimen.

The specimens were thawed and the skin, musculature, and supporting connective tissues were dissected away, and the joints capsule were removed as well (Fig.12).

2.2 Biomechanical measurement

In this study, a novel biomechanical measurement system was built to determine the friction of a sheep joint performing loaded torsional oscillations between the joint surfaces. The friction apparatus system consists of a hydraulic Material Testing machine (858 Mini Bionix II, MTS, Berlin) which is controlled by an application software (FlexTest GT, station Manager Version 3.5C) running on a connected personal computer (Fig 13).

Performing the experiments the joints were set up on the MTS machine, under the control of a program sequence which was defined with the included Multi Purpose Testing Environment (MPT). After mounting the joint specimen between the upper

and lower spine clamps, with zero degree of flexion/extension, the axial load of the machine was nullified as well as the torsion torque.

In order to start the experiment the joint surfaces were contacted by driving the axial hydraulic cylinder of the testing machine manually normal to the joint surfaces.

The following four testing conditions were performed successively: 100N axial load, 200N 450 N and 900 N respectively. In every loading condition the machine performed an oscillating axial rotation movement (torsion) with a saw tooth profile and an oscillation frequency of 0.1 Hz. During 12 oscillation cycles the MPT-software stored the measured values of time, axial torque, axial rotation (torsion angle) and axial load with a repetition rate of 10 Hz.

Fig.13: The friction apparatus system consists of a capture computer and a MTS machine, which includes an upper spine and a lower spine mounting mechanism.

Further data analysis was done with a custom made MatLab routine programmed in the biomechanics lab of the orthopedic clinic.

2.3 OA model preparation

Performing the testing, specimens were thawed, then, the skin, musculature and supporting connective tissues were dissected away. At the meanwhile, the joint capsule was removed as well. The joint of a sheep's wrist was some kind of a compound joint that contained of three parts. To measure the friction of the joint, the part of brachidium joints were fixed by Kirschner wired.

A surgical induced OA model was used in this study, which was better to control the size, the depth, and the position of the defect. This is a new kind of OA model in which the OA is induced by surgically made grooves in the articular cartilage. This novel model has been performed in public (Mastbergen SC 2006).

A full-thickness quadrate osteochondral defect was made through the articular cartilage and into the subchondral bone. Four different sized purely chondral defects , no defect; 4 times 4 mm; 4mm in width and 8 mm in length, and totally defect (about 300mm²), were created on the surface of a part of wrist joint(Fig 14,15,16,17).

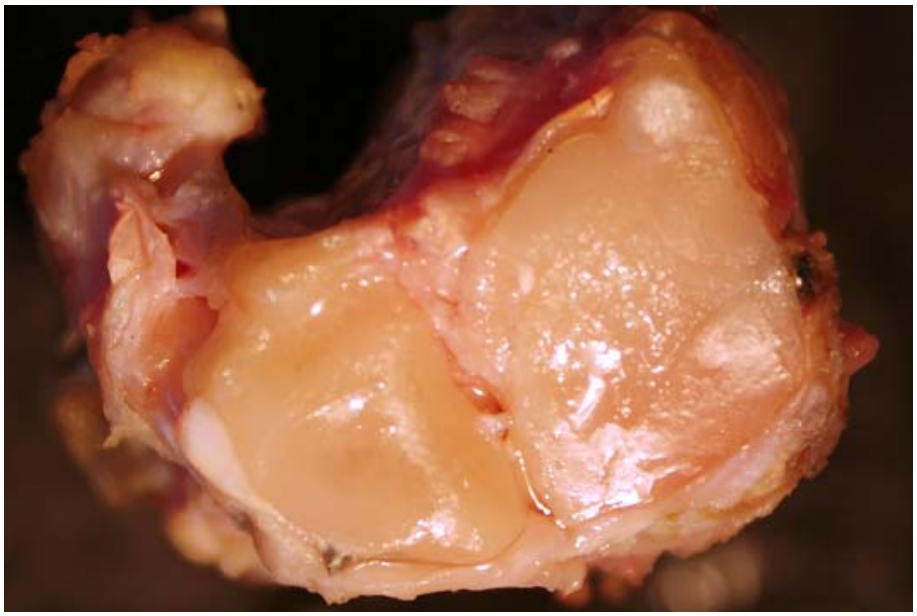


Fig.14: The picture shows one part of a sheep`s wrist joint, and the skin, musculature and supporting connective tissues are dissected away. The joint surface is smooth without any grooves.

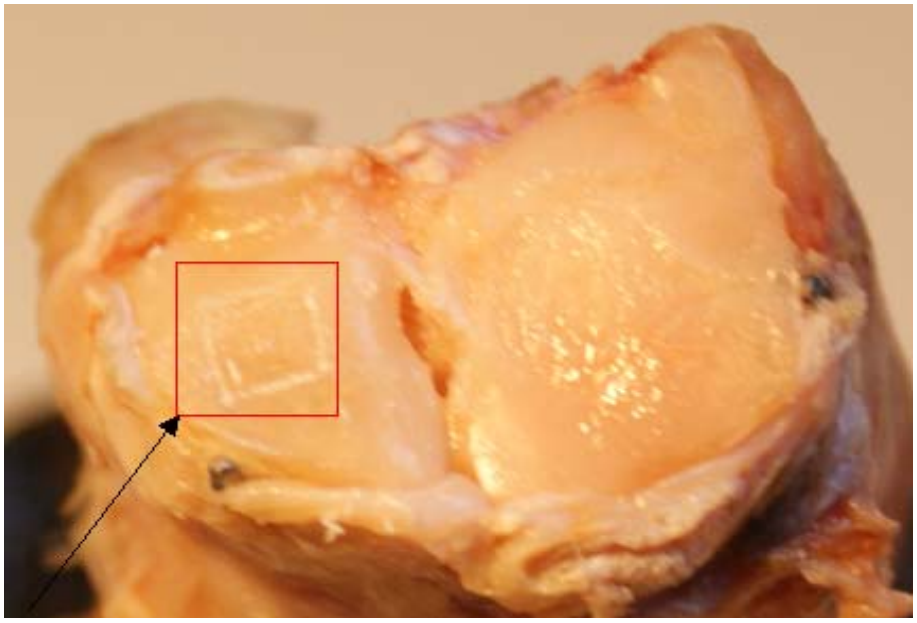


Fig.15: The picture shows a surgical OA model. A 16 mm² chondral defect was created within the lateral facet of the joint surface using a sharp knife.

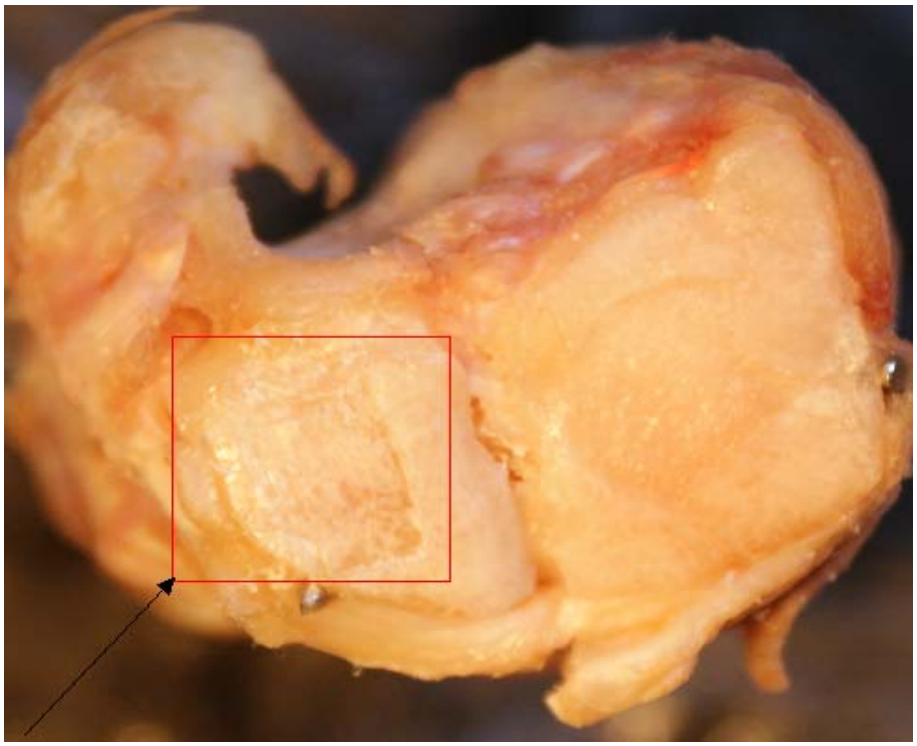


Fig.16: 32mm² purely chondral defect, 4 mm in width and 8 mm in length.

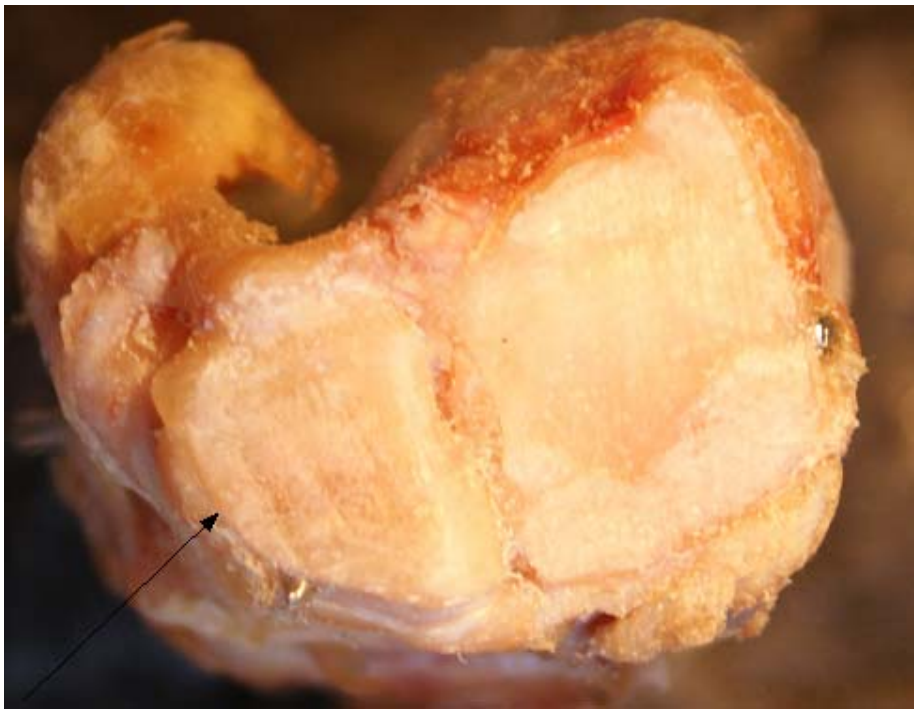


Fig.17: This is a totally defect OA model, all the cartilage of the joint is removed deeply into the subchondral bone. The surface of the joint is no longer smooth any more. The size of the defect area is about 300mm².

2.4 Specimens preparation

To place the joint into the MTS machine, a custom metal frame was used in this study, which could be set up into the MTS machine with screws. A special material was undertaken to fix the bone in the custom metal box (Fig.18).

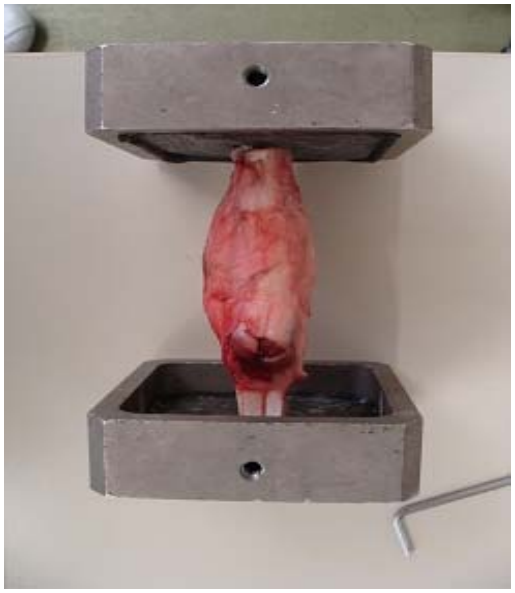


Fig.18: The fixed system, the metal frame is the custom box which could be set up into the MTS machine with screws.

2.5 Lubrication of the joint

To simulate the wrist joint's physiological environment, all joints were kept moist with physiological saline until and during measurement of the biomechanical properties.

2.6 Experimental design

Four different defect groups were designed for this experiment: no defect group, 16mm² defect group, 32 mm² defect group, and total defect group. The OA model joints were investigated in an oscillating torsion experiment applied by a material testing machine with 12 successive loading cycles in axial direction.

Each sample was tested in four different axial loading conditions: 100N, 200N, 450N and 900N axial forces (Chart.1).

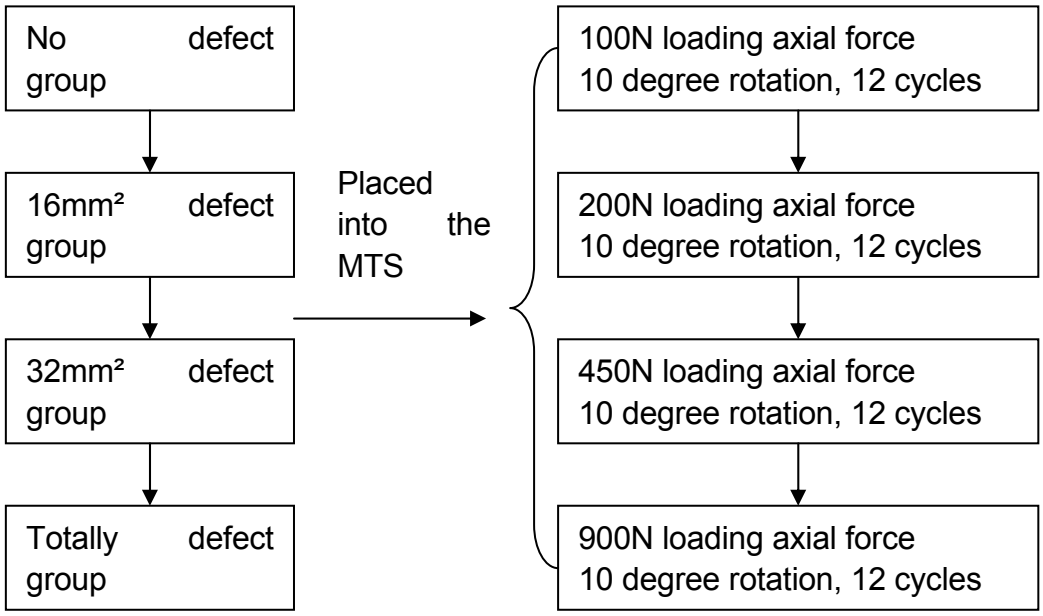


Chart.1: The flow chart of the experiment, there are four defect conditions for one joint. The OA model joints were investigated in an oscillating torsion experiment applied by a material testing machine with 12 successive loading cycles in axial direction.

2.7 Calculation of the frictional energy

The torque and rotational information produced from the material testing machine were used in order to calculate frictional energy dissipation of the oscillating torsion experiment. Calculation was done by a custom made Matlab program. The

principle of calculation and data analysis of the Matlab`s program could be explained with the following diagrams.

In a simple model characterizing dry friction between two moving plane bodies like moving a block from point A to point B, then moving back to point A on a table's surface, the frictional force could be calculated according to the formula:

$F = \mu * W.$

Here, F is the friction force, W is the external normal load, and μ is the friction coefficient.

Chart 2 showed the relationship between frictional force and the distance. The area of the rectangle between the two force/displacement curves represents the amount of energy dissipation by friction.

In a simple disc on disc model, the frictional torque between the two moving surfaces could be calculated as follows:

$T= 2*\mu*R*F/3$

with R radius of the disc, and F normal loading force.

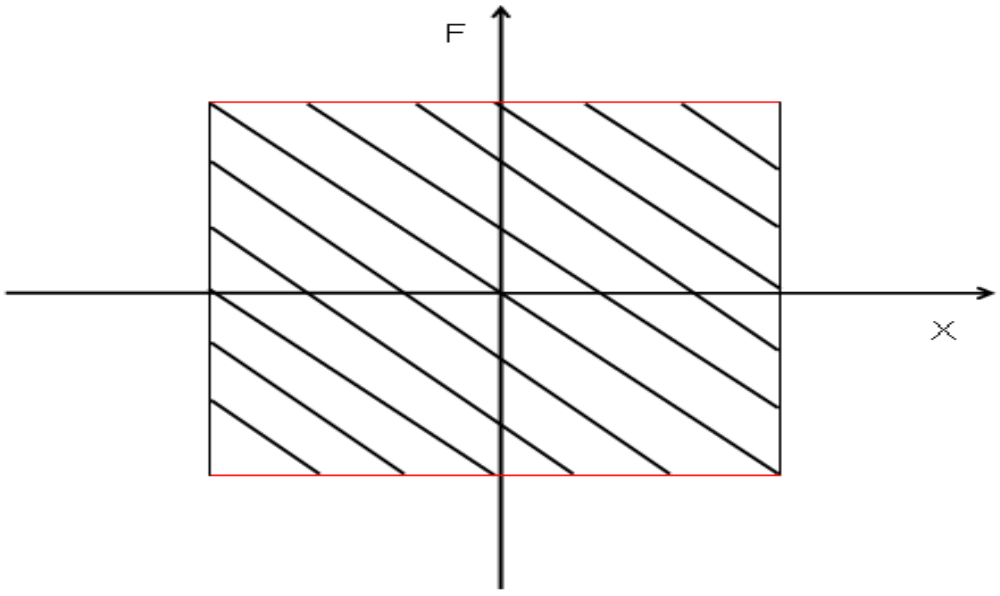


Chart.2 : When a block is moved from point A to point B, then moved back on a surface of a table, the frictional force could be calculated according to the formula: $F = \mu*W$. The red line is the normal force in positive direction and negative direction. The size of the area between the two red lines represents the frictional energy.

Well in a simple linear elastic movement model, like fixing one side of a spring on the wall and pulling the other side of the spring from point A to point B, then moving back to point A. The relationship between the force and the distance could be defined as the formula:

$$F=K*X$$

Where F is the force, X is the distance, K is the elastic coefficient.

According to the formula, chart 3 represented the linear relationship between the force and the distance.

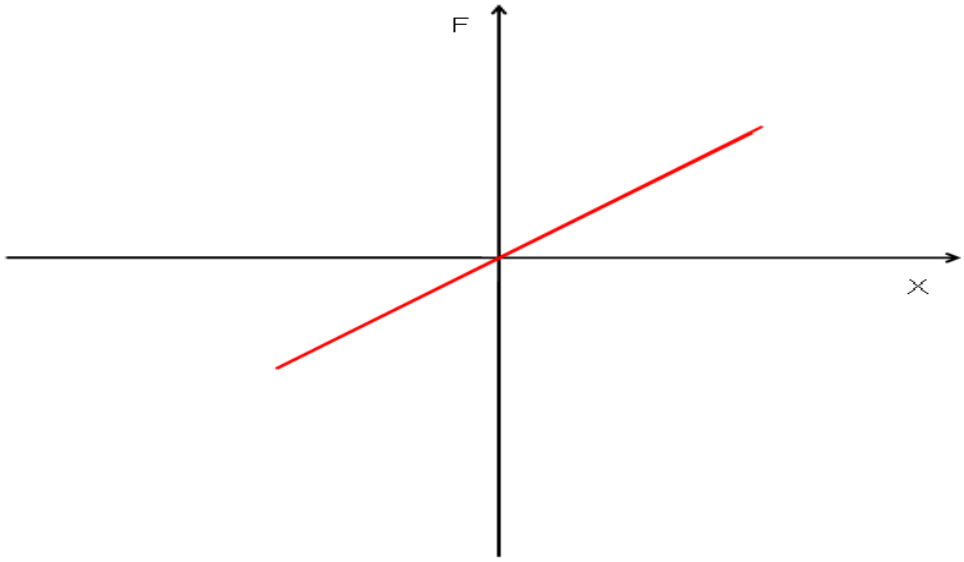


Chart.3: This diagram displays the relationship between the force and the distance. The angle between the red line and X coordinate axis responds to the value of the K.

Usually in nature friction and elasticity are involved both. Thus in general the force/displacement relationship is something intermediate between simple friction and simple elasticity. Moving a body back and forward we get a force displacement relation which looks like chart 4.

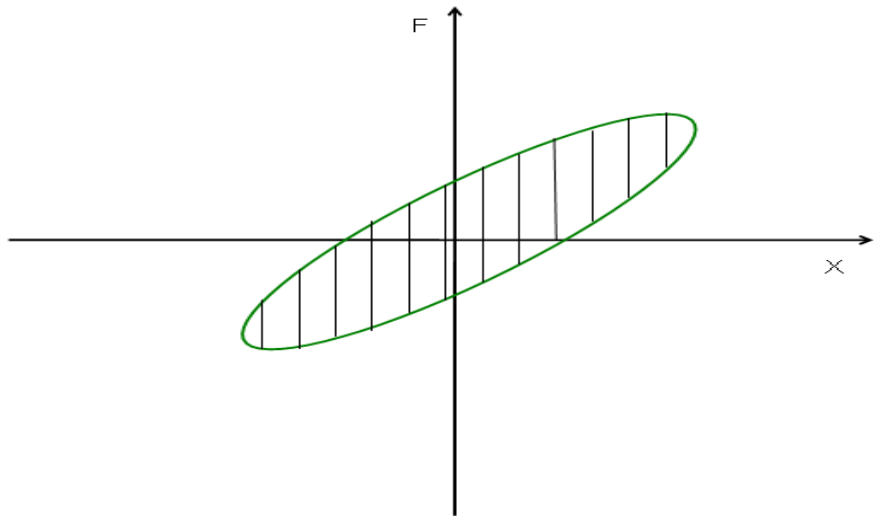


Chart.4: A schematic diagram of combined elastic and frictional movement of two bodies. The area between the tow curves represents the amount of dissipated frictional energy.

For rotational experiments, like we did in the material testing machine, the frictional energy could be calculated analogically by the torque/rotation relationship.

Out of the measured 12 torsion cycles we skipped the first and last one in order to analyze 10 non interrupting continuous cycles. For these ten cycles we calculated the area between the torque/displacement envelopes numerically and determined finally the mean value of dissipated frictional energy per cycle.

Because of the irregular shape of the two joint surfaces in our torsional experiment setup, we have to expect a combined elastic and frictional movement as well. Chart 5 displayed two typical torque/rotation curves from one specimen from no defect and total defect group.

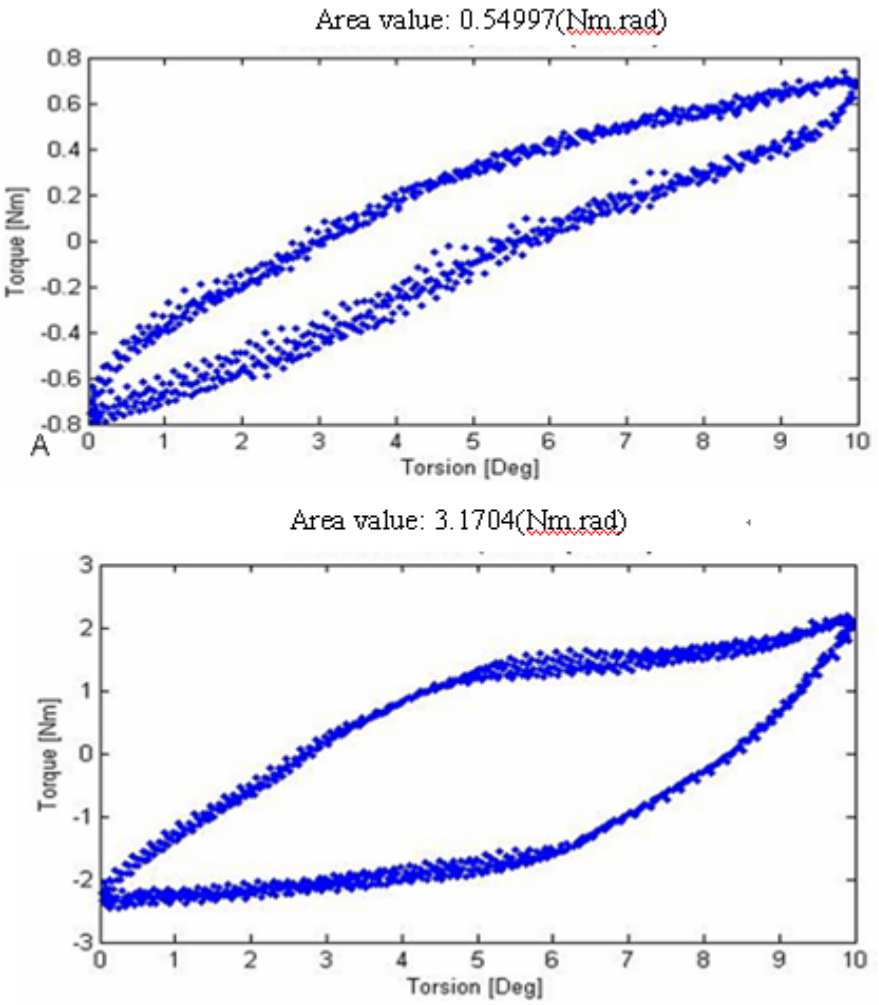


Chart.5: These two diagrams were what we got from one specimen of two groups (loading force was 900N). In the first diagram, the joint is without any defect, well in the second one, the cartilage is totally removed. The area between the curves is the related to the frictional energy, and it is obviously that when the cartilage is completely removed, the area of the curves is bigger than a native one.

2.8 Statistical analyses

Mean values of frictional energy with the standard deviation and the corresponding 95% confidence intervals (95% CIs) were calculated (SPSS 13.0.1). Median values with the 95% CIs were also used to show the tendency of the frictional energy. Because the median values could be used as a measure of location when a distribution was skewed, when end values were not known, or when one required reduced importance to be attached to outliers. It might be more accurate than the mean values because of the fewer specimens in this study.

These values of the frictional energy would also be test by One-Sample Kolmogorov-Smirnov Test, which is a nonparametric tests which could test if the of frictional energy data follows the normal distribution. To compare the mean values, the data would be tested by ANOVA analysis, because the values of interface frictional energy shows normal distribution after One-Sample Kolmogorov-Smirnov Test, and all results are expressed as mean ±standard deviation (SD).

The association between the size of defect area and the frictional energy was tested with the Pearson's correlation coefficient. For all tests, significance is reported if $p < 0.05$.

3 Results

3.1 The normal distribution test of specimens' data

The table1 was got from One-Sample Kolmogorov-Smirnov Test, which was used to test if the values of frictional energy would follow the normal distribution. In the no defect group the value of the P is 0.969; in the16mm² defect group the value of the P is 0.816, in the 32mm² group the value of the P is 0.746 and in the total defect group the value of the P is 0.994. In this test if P>0.05 means that the data have 95% chances follow the normal distribution. It is important to the further data further data analysis, because the one way ANOVA could be used if the data followed a normal distribution.

		No defect group	16mm² defect group	32mm² defect group	Total defect group
N		5	5	5	5
Normal Parameters(a)	Mean	.030579	.044419	.050824	.040411
	Std. Deviation	.0159584	.0266078	.0382934	.0284390
Kolmogorov-Smirnov Z		.492	.634	.679	.425
Sig. (2-tailed)		.969	.816	.746	.994

Tabel.1: This is the table of One-Sample Kolmogorov-Smirnov Test. The value of Z is the statistic of One-Sample Kolmogorov-Smirnov Test. The Sig is the value of P. (a) means the test distribution is normal.

3. 2 The frictional energy's descriptive of statistics

Table 2 shows all the mean values and the standard deviation, whereas the median values of frictional energy in different defect groups are showed in table 3, including the 95% confidence interval. The maximum values, the minimum values can also be seen from table 3. The charts 6, 7, 8, 9 are built following these tables.

Defect Group	Loading Force	Mean	Std. Deviation	N
No defect	100.00	.03057900	.015958366	5
	200.00	.04022240	.024910759	5
	450.00	.08393340	.050059473	5
	900.00	.17211000	.057202867	5
16mm² defect	100.00	.04441860	.026607830	5
	200.00	.06465960	.034318814	5
	450.00	.11848060	.070337722	5
	900.00	.20577600	.101807396	5
32mm² defect	100.00	.04041100	.028439024	5
	200.00	.07058520	.042044460	5
	450.00	.12962200	.070159674	5
	900.00	.22557600	.101632273	5
Total defect	100.00	.05082400	.038293353	5
	200.00	.09127180	.068262646	5
	450.00	.19386000	.093229464	5
	900.00	.30120400	.119488155	5
	Total	.15928995	.126701342	20

Table.2: This is the table of all mean values with the standard deviation. Dependent Variable: Frictional energy.

Defect group	Force	Median	Max	Min	95% Confidence Interval	
No defect	100	0.021697	0.052246	0.015479	0.030549	0.006218
	200	0.031712	0.083506	0.02117	0.051794	0.010542
	450	0.060332	0.15749	0.034107	0.097158	0.026225
	900	0.14525	0.25471	0.061364	0.10946	0.083886
16mm² defect	100	0.026967	0.085762	0.021681	0.058795	0.005286
	200	0.041698	0.10377	0.037565	0.062072	0.004133
	450	0.080603	0.20094	0.056294	0.120337	0.024309
	900	0.17238	0.33682	0.021681	0.16444	0.150699
32mm² defect	100	0.02516	0.089077	0.021729	0.063917	0.003431
	200	0.043942	0.12863	0.039026	0.084688	0.004916
	450	0.089016	0.21002	0.069784	0.121004	0.019232
	900	0.17777	0.34138	0.021729	0.16361	0.156041
Total defect	100	0.058483	0.10911	0.03522	0.050627	0.023263
	200	0.10498	0.17396	0.039459	0.06898	0.065521
	450	0.20118	0.28652	0.0851	0.08534	0.11608
	900	0.35223	0.4348	0.03522	0.08257	0.31701

Table.3: This is the table of median values of frictional energy in different defect groups, with the 95% confidence interval. The maximum and minimum values are also shown in this table.

3.3 Defects and the frictional energy

3.3.1 The difference of frictional energy in all defect groups

One way ANOA was use to test the difference of the frictional energy, in all defect groups. Before using the ANOA test, the homogeneity of the variances should be test at first, because if only the homogeneity of the variances shows no difference then the ANOA test could be used in this study. We used 450N loading force condition data as example to show the statistics. The other loading conditions shows similar result as 450N condition displayed.

Here the Levene test was use to test the homogeneity of variances, because the Levene test showed stability in testing the data. From the table 6 we can see that statistic value of Levene test is 4.083 and the P=0.025(450N loading force). So in

different defect groups the values of the frictional energy shows homogeneity (table.4).

Levene Statistic	df1	df2	Sig.
4.083	3	16	.025

Table.4: Levene test of homogeneity of variances. The Levene Statistic is 4.083 and the P<0.05(450N loading force). So in different defect groups the values of the frictional energy shows homogeneity.

In one way ANOVA, the value of F was used to look if the frictional energy showed differences in all defect groups. According to table, the frictional energy shows significant difference (F=2.001, P< 0.05) in the entire defect groups, when the loading force is 450N (table.5).The similar result could also be obtained in 100N, 200N, 900N loading force conditions.

ANOVA(F)	df	Sig.
2.001	3	0.0154

Table.5: This table shows the statistic of ANOVA test, where F=2.001, p<0.05(the loading force is 450N).

3.3.2 The association between the size of defect area and the frictional energy

In the condition of 450N loading force, a strong correlation is shown between different defect groups and the frictional energy (Pearson coefficient =0.791, P<0.05) (table. 6). The tendency of the frictional energy is displayed in chart 7(using the mean values), and chart 8(using the median values).

The chart 6 presents the dependency of the frictional energy on the defect size (area), of all loading conditions. In this chart mean values are use to display the tendency of the frictional energy.

Chart 7 is built by median values, which might be more accurate than the mean values. Because the median value could be used as a measure of location when a distribution is skewed, when end values are not known, or when one requires reduced importance to be attached to outliers.

		Frictional energy	Defect area
Defect area	Pearson Correlation	1	.791(*)
	Sig. (2-tailed)		.028
	N	20	20
Frictional energy	Pearson Correlation	.791(*)	1
	Sig. (2-tailed)	.028	
	N	20	20

Table.6: SPSS output table for Pearson correlation test between friction energy and defect area for loading condition 450 N. Frictional energy correlates with the defect area (r=0.791).

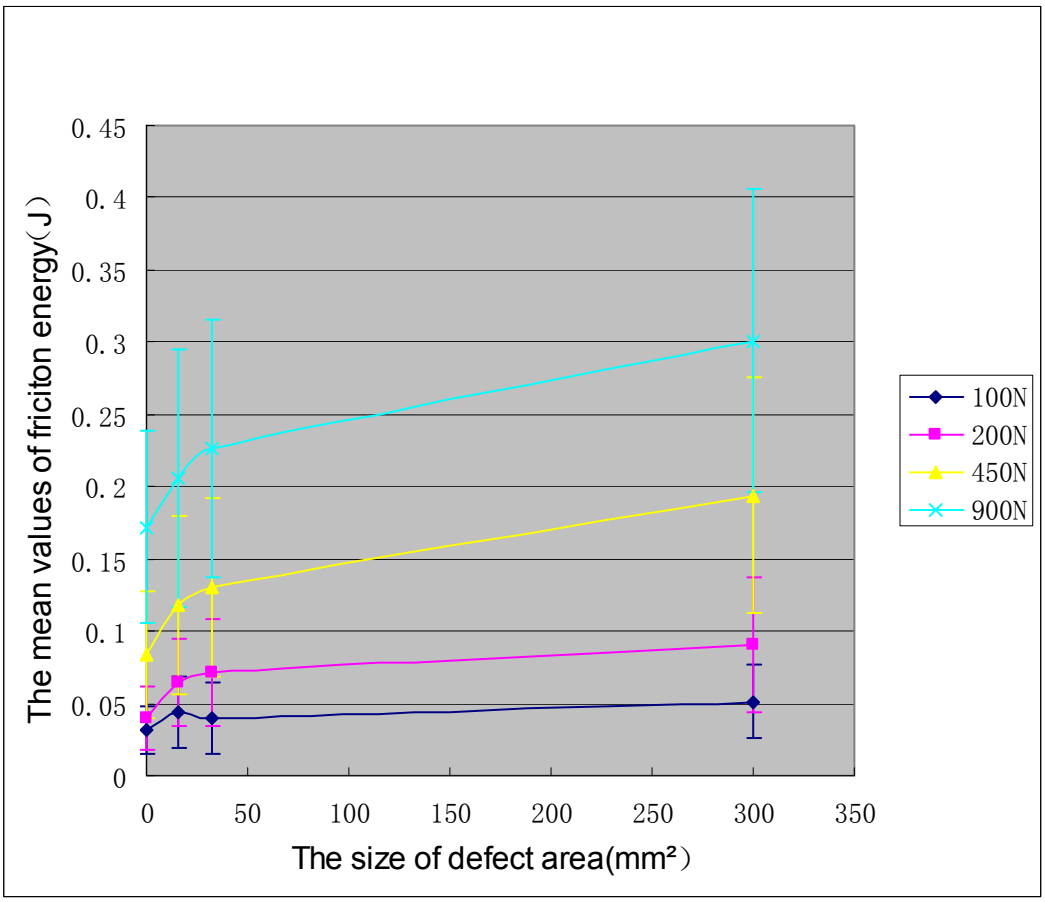


Chart.6: This chart shows the dependency of the frictional energy on the defect size (area).These four curves correspond to four loading conditions Mean values ± standard deviation are presented.

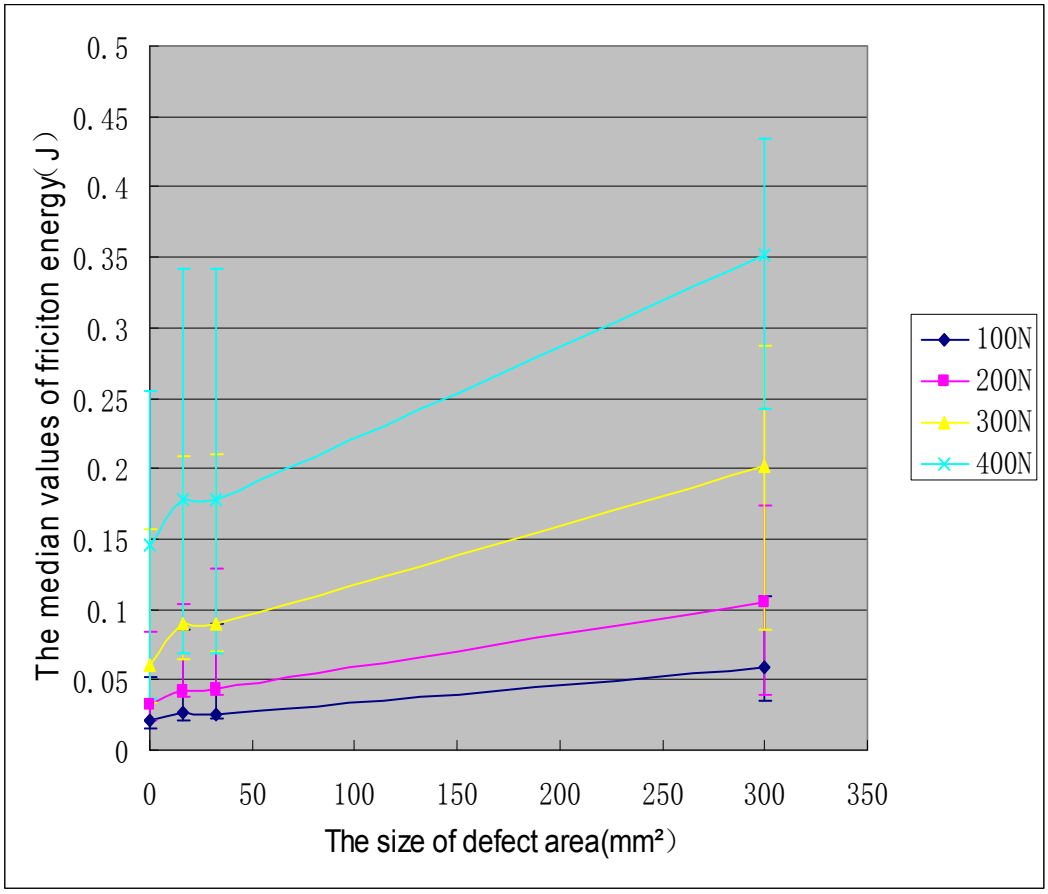


Chart.7: In this chart, these four curves are drawn based on the median values of frictional energy, which also correspond to four loading conditions. The error bars are standing for the maximum and minimum values.

3.4 Loading Force and Frictional energy

3.4.1 The difference of frictional energy in different loading force conditions

Here I used the 16mm² defect groups as an example. Similar results could also be obtained in the other defect groups. In one way ANOVA test, the value of F is used to look if the frictional energy showed different. When the defect area is 16mm², the frictional energy showed significant difference (F=6.113, P=0.006), in different loading conditions (table.7).

A tendency could be observed in the table 2, in the 16mm² defect group the frictional energy increased from 0.044±0.027 Joule to 0.206 ±0.101 Joule, when the axial direction loading forces are increased from 100N to 900N. Similarly, in other defect groups the frictional energy would increase when the axial direction loading forces increased.

ANOVA(F)	df	Sig.
6.113	3	0.006

Table.7: The table shows the statistic of ANOVA (the defect area is 16mm²).

3.4.2 The association between the loading force and the frictional energy

A strong positive correlation is shown between axial direction loading forces and the frictional energy(r=0.730, P=0.00), in 16mm² defect group. It is obviously that when the loading power raised up, more rotated energy is needed to rotate the joint (Table.8).

		Frictional energy	Loading force
Frictional energy	Pearson Correlation	1	.730(**)
	Sig. (2-tailed)		.000
	N	20	20
Loading force	Pearson Correlation	.730(**)	1
	Sig. (2-tailed)	.000	
	N	20	20

Table.8: In 16mm² defect group, the correlation between frictional energy and loading force, correlation is significant at the 0.05 level (2-tailed).

The tendency of the frictional energy curves are displayed in chart 8(using the mean values) and chart 9(using the median values).

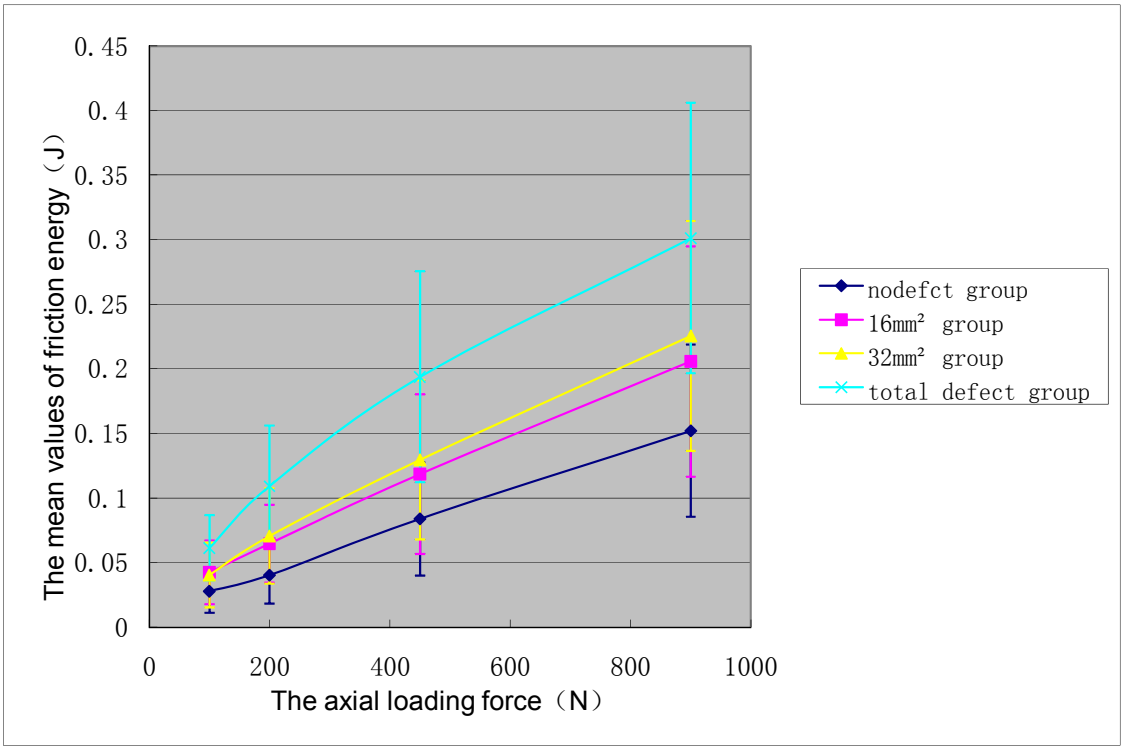


Chart.8: This chart presents the dependency of the frictional energy on the loading force. These four curves correspond to four defect groups. In this chart mean values are use to display the tendency of the frictional energy. The error bars are standing for mean values ± standard deviation.

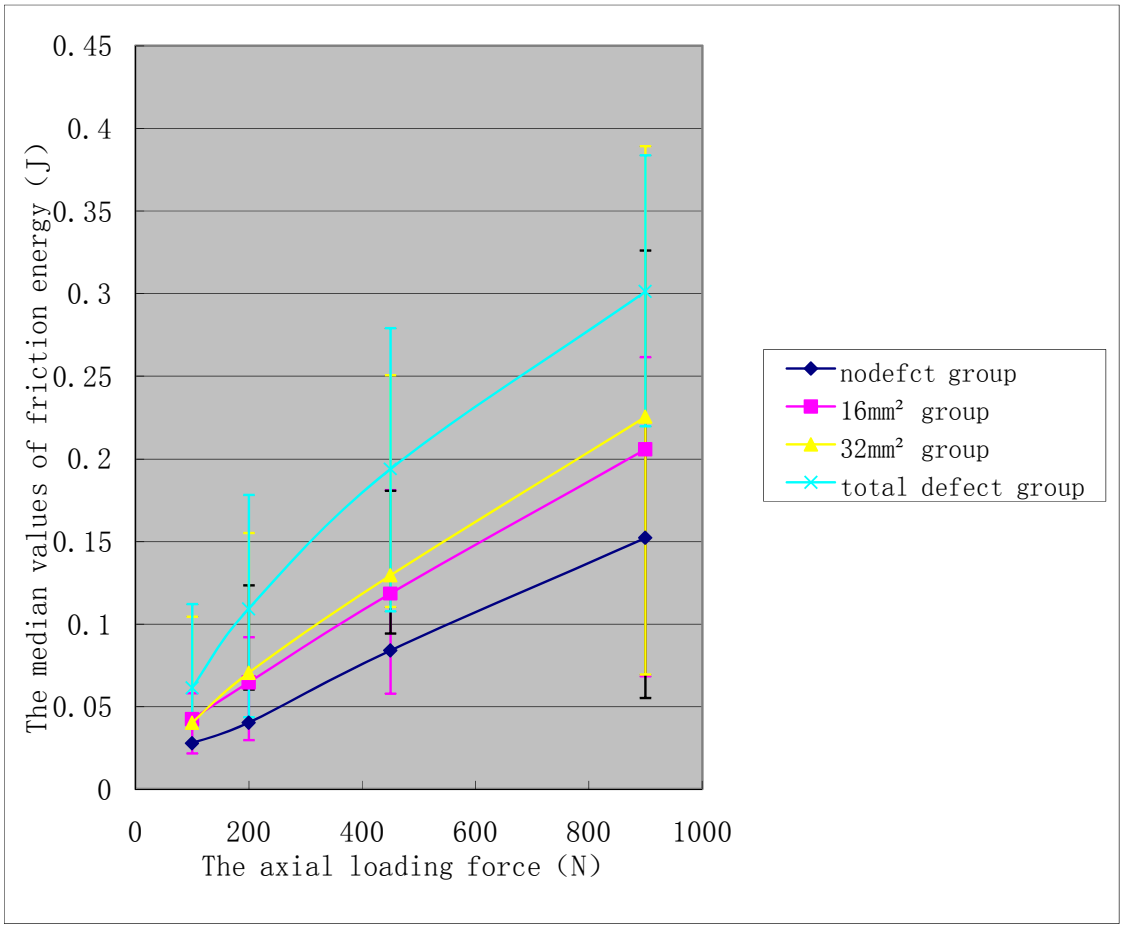


Chart.9: In this chart, these four curves are drawn based on the median values of frictional energy, which also correspond to four defect groups. These curves are nearly straight lines and the error bars are standing for the maximum and minimum values.

4 Discussions

Osteoarthritis (OA) is a normal degenerative joint disease which causes joint destruction, chronic pain, depression, disability, and social in patients. It is considered to be a widespread condition affecting the elderly where 60–90% of over 75 year olds are affected.

Recent progress in biotribology has made valuable insight into the complex nature of friction, wear, and lubrication mechanisms encountered at interfaces of living systems. Biotribology provides a method and design model for the functional motion and properties of articular cartilage. It can also study a lost of other tissues with optimal surface characteristics and properties.

When the biphasic nature of articular cartilage is taken into account, the contact mechanics of the cartilage is an important feature to the tirbology investigation. Paiskar (Pawaskar, Fisher et al. 2010) et al. studied the contact mechanics of the cartilage, they think that whether the surface is in contact or not the fluid flow boundary conditions will change, and the fluid flow will affect the interstitial fluid pressurization. This will decrease or increase the load sustained by the fluid phase, with a direct effect on friction, wear, and lubrication. In experiments, when a metallic prosthesis is used to load on the cartilage, there will not be any fluid flow normal to the surface in the contact region due to the impermeable nature of the prosthesis. well in the natural joint, on the other hand, where two cartilage surfaces interact, flow will infiltrate the interface depended on the pressure difference.

Katta, J. et al. (Katta, J. 2008) used a pin-on-plate machine to measure the coefficient of friction of native and chondroitinase ABC-treated articular cartilage. The results demonstrate the role of GAGs in the compressive and friction properties of articular cartilage and corroborate the need controlling GAGs loss from diseased articular cartilage tissue.

4.1 A novel tribology system

Up to the present, even though some researches have been devoted in tribology, but little is known about friction of the joint especially big animal's joint. To attempt to better understand the joint friction, this novel biomechanical measurement system was established to measure the frictional energy in this study.

4.1.1 The selection of OA model

Researchers have used different animal models of OA to study the effectiveness of different experiments. OA, like arthritis could also be induced by surgical procedures or chemical adjuvants (Janusz, Bendele et al. 2002). Surgically induced OA models may be more clinically relevant than chemically induced models.

Although, there are several drawbacks to surgically induced OA models, including the need for surgical manipulation to induce OA and the difficulty in achieving reproducible levels of severity of arthritis, in this case surgical induced OA model is very easy to control the size, the depth and the position of the defect. Therefore, we used a surgical induced OA model to make the reproducibility of the defect size and stage of OA in wrist joints, and cartilage defects were useful for studying the frictional properties of AC without the influence of intra-capsular ligaments and surrounding tissues.

4.1.2 Advantages and disadvantages of diverse tribology methods

Jay et al. (Jay, Torres et al. 2007) used a pendulum with a mouse knee joint, and calculated the kinetic frictional coefficient μ within the midpoint of joint oscillation. But the disadvantage of the pendulum system is that it can't calculate the frictional force exactly. They estimated the coefficient of friction (μ) by measuring deceleration of the pendulum. This calculation presently neglects aerodynamic drag since the projected area of the pendulum is small, neglects viscoelastic dissipation.

Mueller et al. (Muller, Degreif et al. 2004) constructed a hip stimulator to test the friction coefficients of unipolar femur head made of metal or ceramic against fresh cadaveric acetabula. They calculated the frictional coefficient according to the formula: $M=\mu*F*r$, where M is torque, F is normal force, and r is radius of the femur head. Because of geometrical reasons the friction coefficient μ represents just some kind of mean or reduced frictional coefficient.

But as we know, the joint is much more complicated than a simple plane friction model, and the frictional coefficient was not that easy to be calculated. The declaration of a frictional coefficient maybe mislead, if the relevant current conditions of the tribology system are not designed strictly. As a consequence the friction could not be determined accurately but only approximately, using the presented $M=\mu*F*r$ formula (Davidson and Schwartz 1987).

Therefore, in our tribology experiment, the frictional energy was used to observe the friction properties of the joint not the frictional coefficient, because the frictional energy maybe is more suitable to observe the properties of the joint friction than the frictional coefficient, which implies a simple analytical physical model.

The rational for using the friction energy is the following: There exist simple models for kinetic friction between plane surfaces moving linearly with respect to each other. But here we have to major restrictions:

First, we do a torsional experiment. In this kind of experiments the frictional torque depends from the geometrical shape of the surface, even if they are exactly plane and even if they are ideally circular. Second, joint surfaces in nature are neither exactly plane surfaces nor really circular. Thus moving the joints in an experiment like we did, simple geometrical considerations for the lever arm of the frictinal torque are not applicable as well a the geometrical shape of the joint will produce some elastic forces which can not be distinguished from frictional forces (i.e. the measuring system measures just one force value, or torque value respectively).

For this reason the best way is to characterize the friction of the measured system by the energy which is dissipated by the friction. This can be done very easily and numerically robust by calculating the area between the torque/torsion envelopes during one oscillation cycle by integrating the curves numerically. It is very rebust, because while integrating measurement noise gets corrected automatically in an innocent manner.

4.2 Frictional torque

Frictional torque is the force which delays a disc on disc rotation movement. Frictional torque can occur due to the cyclic elastic or plastic deformation of interlocking surface asperities of a body and counter body. Another contribution comes from the adhesion of atoms and molecules between the two surfaces (Yamamoto, Hashida et al. 2008). The probability of adhesion depends on the mechanical properties and the tendency of atoms and molecules to react chemically with one another.

Like our experiment Unsworth and coworkers(Unsworth 1991) also performed various frictional torque measurements using the hip joint simulator. The contribution of frictional torque of the bone-cement interface was examined in tharies hip replacements (Mai, Schmalzried et al. 1996). So the frictional torque can be used to describe the properties of friction.

4.3 Defects and the frictional energy

From the result we could see that in various defect groups, the frictional energy was entirely different. More important, the table 2 showed us that the mean values of frictional energy in totally defected joints were significantly greater than the unaffected joints in four defect groups. In 100N loading force condition, compared to the natural joints, the friction energy was nearly two times bigger in totally defected joint. These data suggested that in complicated joint movement the frictional energy showed different levels, in different defect conditions.

So the surface properties of the wear themselves may play a decisive role in friction energy, like the mechanical factors (e.g. the geometry of the articulating surfaces and the area of contact between the articulating surfaces, surface properties of the materials, local deformities, load under which the cartilage is compressed, and gliding speed), biological factors (e.g. osteolytic events, formation of giant cells), and chemical (time-dependent) factors (e.g. lubricant, temperature).

Furthermore the Pearson correlation was also significant at the 0.05 level, which means that the defect level had a strong correlation for the friction energy. The

chart 6, 7 discovered the tendency of the friction energy when the cartilage was in different defect levels.

But it was obviously that the relationship between axial loading force and frictional energy was not a very straight line but a curve (chart 6 and 7). It might be explained by two reasons: first the surface of the joint was not smooth when the axial force increased the cartilage would occur a elastic deformation, and the contact area as well. Secondly, the contact area could not be guarantee in different specimens, which might influence the result.

4.4 The loading force and the frictional energy

In this study, different loading forces were used to observe the properties of friction. As we expected before, the friction energy showed a strong statistics difference when the loading force changed. There was also a strong correlation between the friction energy and the loading force.

This result was quit reasonable, because the same conclusion could also be obtained from the fundamental friction formula: $F = \mu * W$. When the cartilage surfaces were damaged the properties of the contact surface would change as a consequence. If the axial force was rise up according to Amonton`s low, the value of the friction force would defiantly became bigger.

The normal force was a very important reason for the OA, because it was also shown to be significant risk factors for the development of OA. More weight means more friction energy was needed to rotate the joint.

It was expected that weight loss would have its most significant effect on OA. Furthermore, in humans, it is the obese (body mass index greater than 30) population with OA that tends to be the focus of research examining the beneficial effect of weight (Christensen, Astrup et al. 2005), (Christensen, Bartels et al. 2007).

4.5 Methods criticism

As previous studies, there are some disadvantages in this novel tribology system. First, the frictional energy can be determined via combined pressure-force measurement plates but not the friction coefficient. Second, even though we treat the cartilage very carefully, the size and the depth of the defect are not easy to control. Thirdly, in the experiment all the tissues like ligaments, meniscus was removed to detect the frictional energy, and obviously it was not the natural condition of a joint, which would influence the result somehow. Finally, another

point for criticism is: With this small sample size it was not possible to distinguish small defect differences by different frictional energy.

4.6 Conclusion

In this study, we established a novel tribology system to estimate the friction of joints, and it was certified to be a useful method to do the tribology research.

4.7 Outlooks

Tribology is a useful method to study the process of OA. This new tribology system that we build can also be applied in friction research, especially the big animal joint or the human beings.

With this system we can do a lot of tribology works, like cartilage-on-glass, rubber-on-glass, cartilage-on-cartilage, cartilage-on-implant, cartilage with different lubrication et al.

The material testing machine we used is established for the application of high forces and torques. We could show that the method is able to discern differences in frictional energy but to detect differences between small defects sizes a load cell which is more sensitive at lower forces and torques should be used.

Future works we will aim at determining the cartilage friction properties with different lubrications, which are important to synovial joints.

5 Summary

Osteoarthritis (OA) is a common degenerative joint disease which causes chronic pain, joint destruction, disability, depression, and social in patients. It is a widespread condition affecting the elderly where 70–90% of over 75 year olds are affected.

In the very beginning, such as the knee, OA can be characterized by the gradual loss of articular cartilage (AC) within synovial joints. The biochemical changes in cartilage are characterized by the following: possible changes in the size of collagen fibril, reduced proteoglycan (PG) concentration and aggregation of PG, In the most extreme cases, the cartilage may be worn off completely, resulting in bone-on-bone surface rubbing.

Many researchers have studied the coefficient of friction of articular cartilage（AC）using a variety of methods, especially with the tribology method. Functional biotribology is a useful way to better understand how and why cartilage becomes osteoarthritis. Functional biotribology emphasizes surface characteristics and properties in the joint and at the mean while lubricant substances can reduce friction and wear of interacting surfaces.

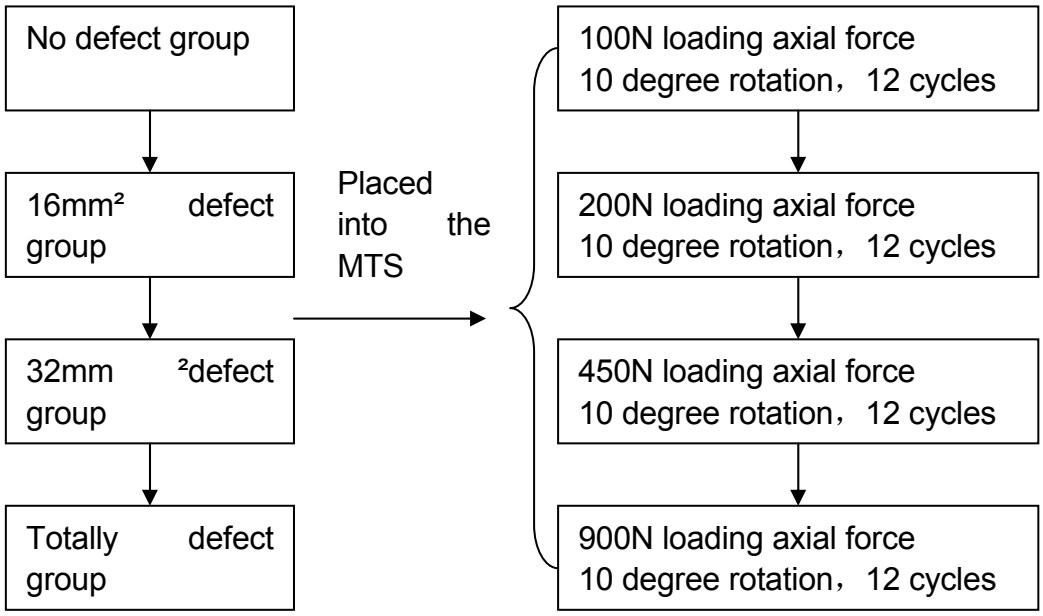
Functional biotribology mainly study friction, lubrication, and wear. Functional biotribology emphasizes surface characteristics and properties in synovial joints and at the mean while lubricant substances can reduce friction and wear of interacting surfaces.

This research will mainly focus on the biotribology of articular cartilage, and aim to build a novel in vitro experimental model, which can be applied to study fundamentals of cartilage friction, wear and lubrication. We hope such new tribological model's systems hold a distinct advantage to understand cartilage natural behavior, degradation processes, and evaluate various cartilage treatment therapies.

In this study, a novel biomechanical measurement system was built to determine the friction of a sheep joint performing loaded torsional oscillations between the joint surfaces. A surgical induced OA model was used, which was better to control the size, the depth, and the position of the defect.

Four different defect groups were designed for this experiment: no defect group, 16mm² defect group, 32 mm² defect group, and total defect group. The OA model joints were investigated in an oscillating torsion experiment applied by a material testing machine with 12 successive loading cycles in axial direction. Each sample

was tested in four different axial loading conditions: 100N, 200N, 450N and 900N axial forces(Chart.1).



This the flow chart of the experiment, there are four defect conditions for one joint. The OA model joints were investigated in an oscillating torsion experiment applied by a material testing machine with 12 successive loading cycles in axial direction.

Because this was not a simple model for kinetic friction between plane surfaces moving linearly with respect to each other, the frictional energy was used to observe the friction properties of the joint not the frictional coefficient.

From the result we could see that the frictional energy showed significant difference in the different defect groups. A strong correlation was showed between different defect groups and the frictional energy. When the size of the defect became bigger, more frictional energy was needed to rotate the joint.

Furthermore in one defect group, the frictional energy showed significant difference in different loading conditions, and the friction energy and the loading force also presented a linear correlation.

Anyway, this novel tribology system was established to estimate the friction of joints, and it was certified to be a useful method to measure the tribology properties of joint, especially the joint of big animal. Thought this system the influence of the defect and the loading force of the joint was presented.

With this system a lot of tribology works can be done easily, like cartilage-on-glass, rubber-on-glass, cartilage-on-cartilage, cartilage-on-implant, cartilage with

different lubrication. Future works should aim to determine the cartilage friction properties with different lubrications, which are important to synovial joints.

6 List of Figures

7 Abbreviations

OA	Osteoarthritis
GAGs	Glycosaminoglycans
AC	Articular cartilage
PG	Proteoglycan
SZP	Superficial zone protein
MPT	Multi Purpose Testing Environment
SPSS	Program for Social Sciences
MTS	Material testing machine (858 Mini Bionix II, MTS, Berlin)

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