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Synovial Joint Lubrication – does nature teach more effective engineering lubrication strategies?

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Abstract

Nature shows numerous examples of systems which show energy efficiency, elegance in their design and optimum use of materials. Biomimetics is an emerging field of research in engineering and successes have been documented in the diverse fields of robotics, mechanics, materials engineering and many more. To date little biomimetics research has been directed towards tribology in terms of transferring technologies from biological systems into engineering applications. The potential for biomimicry has been recognised in terms of replicating natural lubricants but this system reviews the potential for mimicking the synovial joint as an efficient and durable tribological system for potential engineering systems. The use of materials and the integration of materials technology and fluid/surface interactions are central to the discussion.

Introduction

Lubrication technology has for the last 6 decades relied to a great extent on chemical additives added to oils to provide important tribological functionality, namely wear protection and friction reduction. In the boundary lubrication regime, the system is characterized by intimate contact between the asperities of the tribocouple and the tribochemical reactions that occur as a result of this contact are crucial for enabling the lubricant to become functional.

Radical changes in lubricant additive technology are being forced on formulators, primarily through changes in legislation, and because of this there is a need for alternative approaches towards effective lubrication or more efficient tribological systems. Incremental steps are being made to get towards environmentally-acceptable solutions to achieve target CO_2 emissions, alongside retained engine performance but these are unlikely to deliver any more than an incremental move to keep in line with the shifting targets imposed by government. As examples:

- The level of P has progressively decreased from 0.12wt% in 1993 for ILSAC (International Lubricant Standardization and Approval Committee) GF-1 oils, to 0.1wt% in 1996 and 2001 (GF-2 & 3) and it will be further reduced to 0.08wt% when GF-4 is introduced.
- The CHON concept (lubricating engines with only Carbon, Hydrogen, Oxygen and Nitrogen) has been introduced by formulators and some progress in this respect has been made

- Alternative additives, some based on e.g B, are being introduced to replace some of the functionality of P. Future legislation on B-containing compounds is not yet clear

Engineers are increasingly turning to nature for effective solutions to some of the most challenging technological problems – perhaps because nature provides systems which are energy efficient, normally elegant and durable. The field of biomimetics has made an impact in the fields of robotics, biomedical devices, sensors and several others.

In tribology there has been progress made towards using lubricants derived from nature [1-4] and replication of natural lubricants [5,6]; the work being driven by the need to provide “green” lubrication strategies. Also, in tribology there has been a lot of effort expended in the last decades to understand fully how synovial joints work and the field of biotribology is enormous and growing. However, the drive in biotribology is to enable more efficient replacement joints to be developed. Both the understanding of the natural joint and the understanding of how the artificial joint operates attract much attention from biotribologists.

In this paper the focus is to consider biomimetics, and in particular mimicking the synovial joint, as a means of making advances towards more effective engineering tribological systems – this is in contrast to consideration given to the joint in biotribology where the main focus is to produce more effective joint replacements.

The main difference between man-made and natural lubricants is that the former are usually “oil-based” while the latter are “water-based” systems. Use of water for lubrication, instead of oil, has many benefits (most notably environmental) and nature is a great tutor to show us how to reach this. In the field of effective natural lubrication, one of the most striking examples of the possibility for bioinspiration is the inspiration from the lubrication of mammalian joints. The effective lubrication in this system is expressed by the low friction which is found to be in range of 0.002-0.006. Considering the low speeds involved, this friction is much lower than would be expected using existing technologies. To illustrate this difference, Figure 1 shows the friction values reached in mammalian joints compared to the friction values that are reached in tribological systems (e.g. in the internal combustion engine).

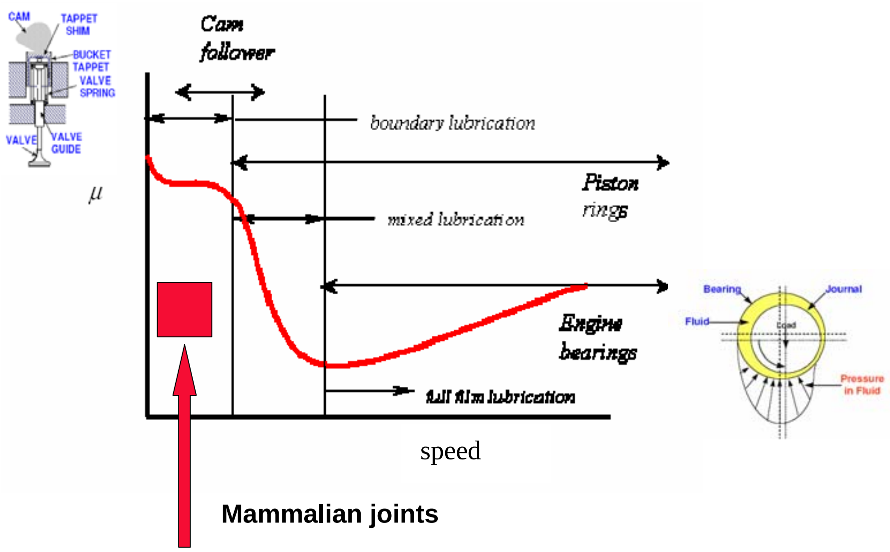


Figure 1. Friction obtained in mammalian joints in scale with the friction obtained in internal combustion engine tribological systems [7].

The tribological characteristics, friction and wear, of a system are a result of many parameters involved in the contact. Just to mention few, these are: contact pressure, speed, viscosity of the lubricant, roughness of the materials in contact, physical properties of the materials in contact etc. Table 1 shows the tribological parameters in joints in comparison with engine components.

	Joints	**Bearings**	**Piston rings/cylinder**	**Cam/cam follower**
Lubrication	Sliding/rolling	Rolling	Sliding	Sliding/rolling
Lubrication regime	Hydrodynamic/ Boundary lubrication	Hydrodynamic/ EHD	Mixed/hydrodynamic	Boundary/EHD lubrication
Speed	0.03-0.3 m/s	15 m/s	0-25 m/s	7 m/s
Contact pressure	Max 18 MPa	60 MPa	10 MPa	Max 1 GPa
Temperature	25-40 °C	120-150 °C	125-200 °C	~ 100°C
Lubricant properties	Synovial fluid – thixotropic	Oil – when in EHD thixotropic	Oil – when in EHD thixotropic	Oil – when in EHD thixotropic

Table 1. Tribological parameters in joints and comparison with the ones in engine components.

It would appear that the friction values reached in joints can only be reached if there is hydrodynamic (full film) lubrication as is the case when there is a thick film between the rubbing surfaces and the frictional response is dominated by the bulk viscosity of the liquid. However, the slow speeds that characterize joint movement suggests that it is extremely difficult for a film to be formed and maintained. At these low speeds, in engineering systems, boundary lubrication will occur; this being the regime where the thickness of the lubricating fluid film is smaller than the height of the asperities and effective lubrication is provided by tribochemical films formed on the asperities. This implies one of two things: hydrodynamic lubrication is achieved as a result of the interaction between the articular cartilage and the synovial fluid or that there is an amazingly effective boundary lubricant present in synovial fluid. It could however, be a combination of both. If boundary lubrication is achieved then the friction values suggest that boundary films formed in joints are much superior (i.e. lower friction) to their synthetic counterparts. Despite extensive research being done in analysing the lubrication system of the joints, there is still a great debate about the definite mechanism(s) of lubrication in synovial joints [1,8].

Potential Benefits from Successful Mimicking of Synovial Joint Mechanisms

The purpose of this paper is to critically assess the mechanism of lubrication in this very effective lubricated system and assess the possibility of development of synthetic materials and engineering systems that would mimic the lubrication in joints.

Before continuing in this respect it is important to consider what benefits (in terms of fuel economy and emissions reduction) could be realized should a successful attempt to mimic the synovial joint be forthcoming.

Quantitatively what are we to achieve if we can attain the drastic reductions in friction coefficient shown schematically in Figure 1? Fuel economy and frictional losses in internal combustion engines are inextricably linked and so the major benefit in reducing friction is to increase fuel economy. Of course to perform robust calculations on the increases in fuel economy requires a complete analysis of the vehicle dynamics and engine efficiency but a reduction of the coefficient of friction from the typical engineering boundary lubrication values (assumed to be in the order of 0.12) to the typical values seen in the synovial joint (estimated to be 0.004 [9]). It is also the case that should lubrication be based on the concepts of the synovial joint that the liquid lubricant phase will have lower viscosity – benefiting fuel economy in the hydrodynamic regime. Lower viscosity oils SAE 20 and SAE 10 lead to increases in fuel economy of 3 and 4.4% respectively [10]. For CO_2 emission reduction achievable annual targets for these lubricants would be 67kg and 97kg respectively (from a total of approximately 2250kg annually).

It is clear that the potential offering of a significant increase in fuel economy is the main incentive to mimick the synovial joint but of course there are other major considerations in relation to durability which would be paramount should lubricant viscosity be reduced. In this respect it is useful to compare the durability of natural systems (e.g synovial joint) and the internal combustion engine (e.g in a passenger car) and the durable “life” of each. The synovial joint can operate efficiently in the vast majority of cases for over 75 years (exhibiting extremely low friction and wear). This equates to more than 1 million loading cycles per year [8] and more than 75 million over the lifetime. If this is compared with the average IC engine in a passenger car over 100,000 miles the total number of cycles would be 220 million. Other biological systems (involving tribological action) can demonstrate durability for several orders of magnitude greater numbers of cycles than the synovial joint – the heart valve leaflets being one such system [8] which can operate effectively for up to 5 billion cycles.

What Do We Have to Mimic?

Central to being able to mimick the synovial joint functionality is a thorough understanding of its tribology and from this developing design concepts that will enable the biological system to be replicated for technological applications. One point should be clarified at this stage – it has been discussed previously in this paper that the tribological conditions in terms of load, temperature, speed etc are all vastly different in the synovial joint and an IC engine (or indeed other technological applications in tribology). It is in the *functionality* that the similarities exist and that the potential for biomimcry exists. Translation of biological materials into the technological application in this case is unfeasible and so the major challenges are (i) designing the materials which will function as the components of the synovial joint do under tribological conditions (ii) assembling a "system" to perform in the required tribological environment but display drastically lower friction coefficients comparable with the synovial joint and with the required durability. This is not trivial and the first discussion towards this is embedded in the remainder of the paper following a discussion of how the synovial joint works.

The major elements of the natural synovial joint, shown in Figure 2, are [8]:

- The underlying bone
- The articular cartilage (in the knee, the meniscus)
- The synovial fluid and
- The tissues that constrain and articulate the joint, the ligaments, tendons and soft tissue capsule.

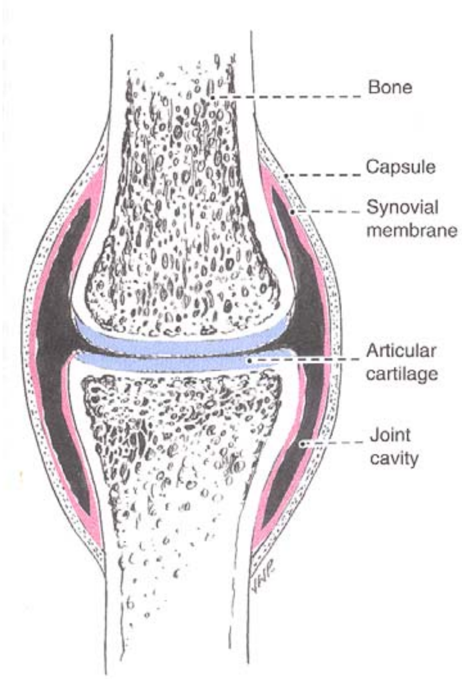


Figure 2. Synovial joint capsule

Articular Cartilage

Articular cartilage (AC) is a soft porous composite material, white with smooth and shiny surface. The main constituents of AC are collagen, proteoglycans and water. Collagen and proteoglycans in the cartilage form interpenetrating networks that create a strong solid matrix. The pores containing the water constituent have been estimated to have a diameter of ~60Å. Collagen represents 50-75% of the dry weight of AC while proteoglycans 15-30% [11,12]. There is around 80% water in the cartilage. AC is aneural, meaning that there is no blood supply and alymphatic [11], encouraging the possibility of building an artificial structure that would mimic AC structure and characteristics.

The cartilage is bonded to the bone, Figure 3, and behaves as a thin-layer cushion contact [8]. As shown in Figure 3, the articular cartilage is reported to have three layers [13]:

- small closely packed fibres parallel to the surface
- an intermediate layer with an open mesh work of S-shaped fibres approx. 900nm in diameter. It is suggested that they were arranged in this manner to allow deformation for energy absorption.
- in the deep zones of the cartilage there were large fibres (1400nm diameter) arranged radially and running into the subchondral bone.

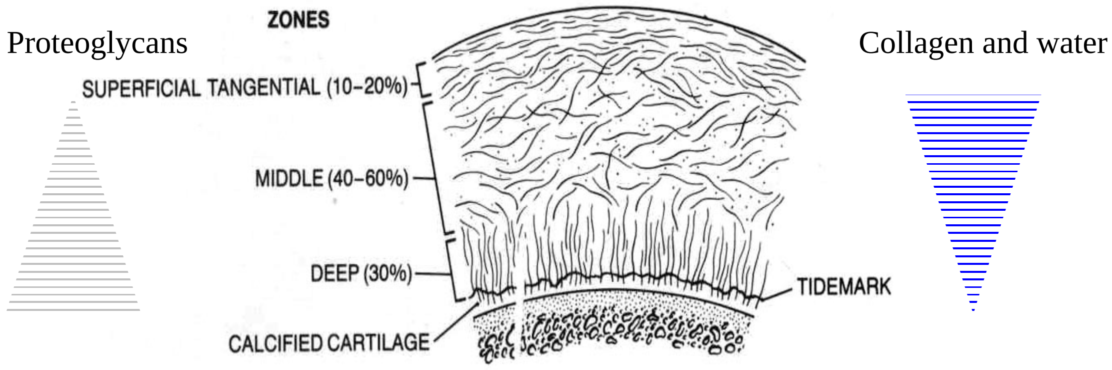


Figure 3. Internal structure of the articular cartilage and schematic representation of proteoglycans, collagen and water concentration with depth [13].

As can be seen in Figure 3 the collagen fibre orientation varies with depth from the articular surface. At the articular surface the collagen fibres are orientated parallel to the surface, in the middle zone the orientation is at an angle to the surface and in the deep zone the collagen fibres have orientation perpendicular to the bone interface, with the fibres extending into the bone for effective anchorage. Bone and AC are materials with high and low modulus of elasticity and their junction is a good example [14] of bonding materials with different mechanical properties; something not commonly seen in tribological applications.

The major non-collagenous components of the solid phase of AC are proteoglycan macromolecules. The concentration of proteoglycans is lowest near the AC surface and increases with depth. The proteoglycan macromolecules consist of a protein core in which 50-100 glycosaminoglycans chains (chondroitin sulphate and keratan sulphate) are bonded to form a bottlebrush-like structure. These structures are then aggregated to a backbone of hyaluronic acid, Figure 4, to form a macromolecule with a weight up to 200 million and a length of approximately 2 μm [12,15].

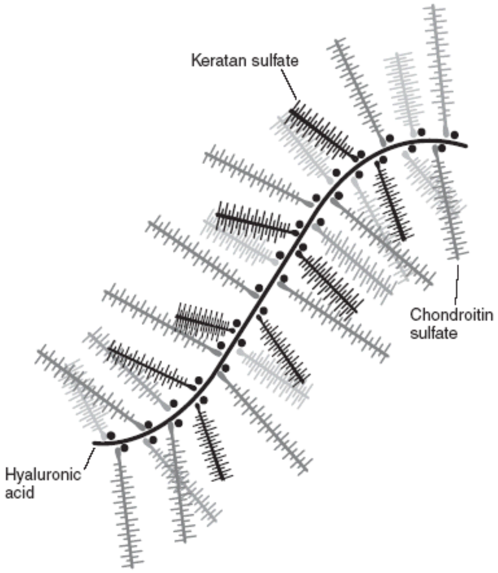


Figure 4. Proteoglycan structures aggregated to a backbone of hyaluronic acid [12].

Proteoglycans are negatively charged and attract the hydrogen atoms (Figure 5) of the water molecules, hydrating the zone where there are proteoglycans. Absorption of water from the synovial joints results in swelling of the collagen fibrils [11,12].

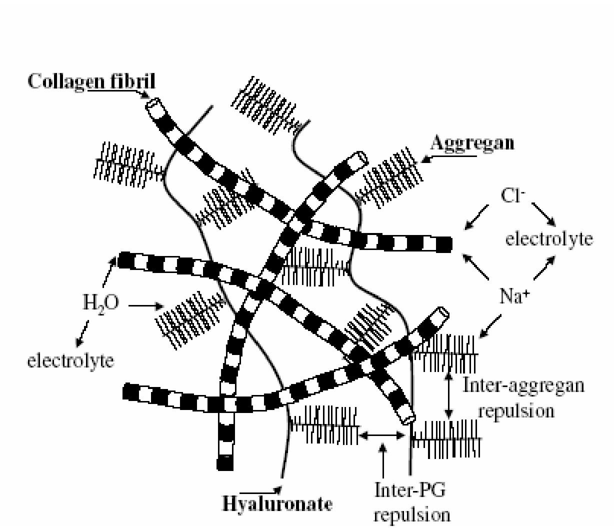


Figure 5. Schematic structure of the articular cartilage.

The compressive properties of cartilage are provided partly by the proteoglycans that resist compression because glycosaminoglycans chains repulse each other due to their negative charges [11]. These characteristics of proteoglycans, water attraction and repulsion from each other, provide the viscoelastic properties of articular cartilage, very important properties for effective lubrication.

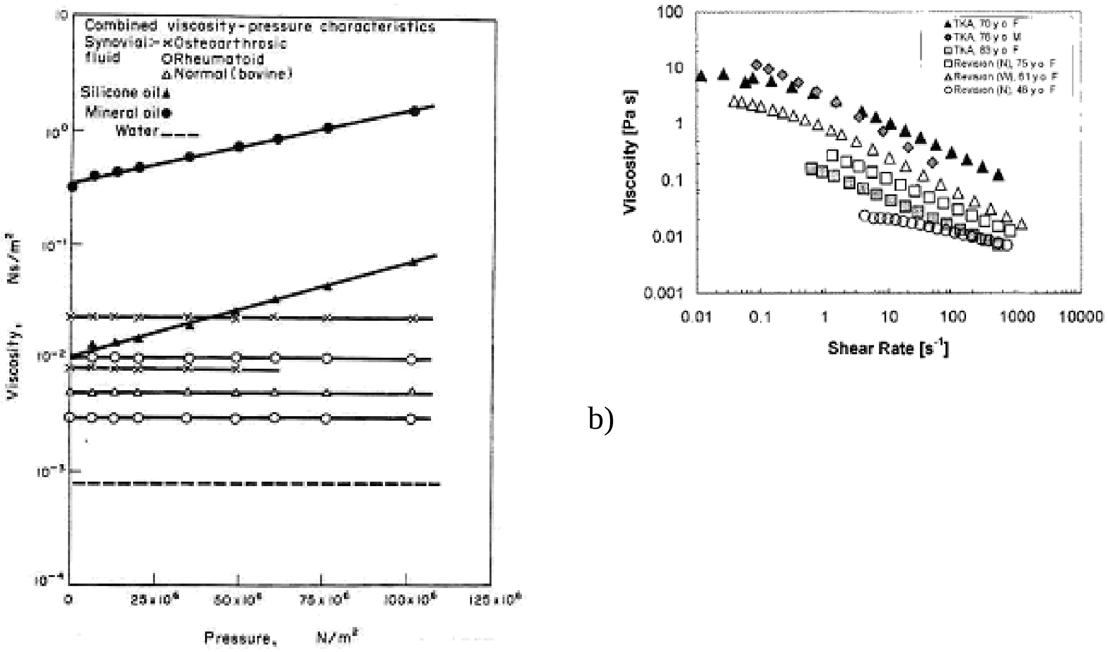
Synovial fluid and its rheological properties

Critical to the successful long-term tribological function of synovial joints, besides the mechanical properties of AC, is also the nature of the synovial fluid. Synovial fluid is clear to yellowish and is stringy. It resembles egg white, and it is this resemblance that gives joints their name, synovia, meaning “egg white”.

Synovial fluid is essentially a dialysate of blood plasma with chief constituent being water and containing:

1. long chain protein molecules
2. hyaluronic acid and
3. phospholipids.

In the existing tribological systems, for good full film lubrication the rheological properties of the lubricating fluid are of great importance. Synovial fluid at different pressures shows no significant change of viscosity (Figure 6a) a factor that proves to be a critical difference when comparing to the positive pressure-viscosity coefficients in engineering oils [16]. An increase of shear causes shear thinning (Figure 6b) and the decrease of viscosity with increased shear rate [17].



b)

a)

Figure 6. Rheological properties of synovial fluid, a) pressure-viscosity [16] and b) shear-thinning properties [17].

Another important property of synovial fluid is the stress increase in time during steady shear – ***rheopexy*** [18]. This property is attributed to protein aggregation and it is thought to strongly enhance the viscoelastic character of synovial fluid.

Synovial joint lubrication mode

The results of the experimental work done by Krishnan *et al.* [19] suggest that interstitial fluid pressurization is a primary mechanism in the regulation of the friction response of articular cartilage. By supporting the majority of the load transmitted across the contact interface, the interstitial pressurization reduces the load supported by the contacting collagen-proteoglycan matrix and opposing surface, considerably reducing the frictional force relative to the total contact force. However, McCutchen pointed out that the problem with the fluid-film models is that, if anyone stands for 30 min, all fluid is going to be “squeezed out” from between the load-bearing articular surfaces of the knee. However, in the healthy people, the knee joint is still perfectly lubricated the moment movement starts. This suggests that boundary lubrication could also occur. In the work of Hills [7] the effects of the components of synovial fluid ingredients are reviewed. Hyaluronic acid has for many years been considered to be the main lubricant, but it has a negligible load bearing capacity; the load bearing of hyaluronic acid is shown to be only 0.4 kg/cm^2, which is very low when compared with 3 kg/cm^2 for the normal load on the adult knee joint when standing. Hyaluronic acid has an important role in retaining water. The centrifugation of the synovial fluid resulted in its separation into two layers:

- a “hyaluronate” layer and
- a “proteinaceous” layer.

Results from friction tests have pointed to the protein (lubricin MW 227500) as the vital load bearing ingredient residing in the “proteinaceous” and *not* in the “hyaluronate” layer. 11 percent of Lubricin was found to be surface-active phospholipid (SAPL). 86% of these macromolecules are characterised but of the remaining 14%, 12% was subsequently identified as Surface Active Phospholipids (SAPL), raising the issue whether lubricin is the lubricant *per se* or whether it simply acts as the macromolecular water-soluble carrier for these small (Molecular Weight approx 734) surfactant molecules that are otherwise very insoluble in water [5].

The lubrication system in the joint and moving sites *in vivo* appears to consist of a fluid in contact with sliding surfaces coated with an oligolamellar lining of Surface Active PhosphoLipids (SAPL). As the outermost layer, this lining provides boundary lubrication and imparts the *hydrophobicity* characteristics of these surfaces when rinsed free of synovial fluid, which appears to contain a wetting agent to promote hydrodynamic lubrication. Thus, the fluid film provides lubrication wherever it can support the load but, with physiological velocities being so low by engineering criteria, *SAPL* would appear to play a major role as a boundary lubricant, especially in load bearing joints [5,20,21] although this theory is challenged by other researchers [22]. The capability of SAPL to act as a boundary lubricant was first recognised in the thoracic cavity, in which frictionless sliding of the lungs is needed to reduce the work of breathing [23]. Researchers have speculated that SAPL is the boundary lubricant found wherever tissues need to slide over each other, also acting as an antistick agent [23].

Moving Towards a Technological Solution

Key to being able to use biomimetics principles for improving tribological design is the realization that it is the functionality that is to be mimicked. Changing the tribological "system" to mimick the synovial joint is potentially the most fruitful way forward – using all the attributes of what is an energy efficient and durable tribological system to develop new technological designs. In Table 2 some ideas on mimcry and the main constituents are presented. This is an initial attempt as predicting the way forward for biomimetics in lubrication/Tribology and outlines some of the most attractive areas of research that could be exploited. There is great potential for development of lubrication strategies involving (a) porous materials (b) aqueous functional fluids (c) deformable solids and design of a system using biomimetic principles will require serious studies in all of these areas.

Elements of the Frictional System	**Properties**	**Function**	**Potential Replacement**	**Potential Mimic System**
Material: *Articular cartilage*	porosity	enable interstitial flow of fluid	metallic and polymer cellular materials	High elasticity and porous materials lubricated by water based fluid.
	elasticity	structure deformation for energy adsorption	soft metals, polymers, rubber	
	fluid attraction	fluid swallow under load removal	hydrophilic structure	
	stiffness	limit the structure compaction under the load by collapse of the upper layer	controlled structure with variable porosity	
	permeability	upper layer more permeable to exude the fluid faster	chemical functionalisation	
Liquid: *Synovial fluid*	No viscosity/pressure dependence	Viscosity of synovial fluid does not change significantly with pressure	Broad range of fluids – potential for water lubrication	
Additives: *SAPL (?)* *Hyaluronan*	Low friction surface film	Reduce friction when the fluid film breaks down and there is surface contact	Polyelectrolyte multilayers Any low friction film formation additive	
	Viscoelastic	Hyaluronan – resist shear flow and strain linearly with time when a stress is applied.	Additives who having viscoelastic properties. (May not for the application of water lubrication)	

Table 2. Mimicry of the functionality of the synovial joint – some ideas for use of biomimetic principles in tribology

Concluding comments

The unique functionality of the synovial joint has been described in an attempt to draw out some of the potential for biomimetic-based design in tribology using an appreciation of the synovial joint as a “system”. The paper discusses potential strategies to mimic the functionality of the synovial joint and identifies fruitful research areas to achieve the potential gains from a biomimetic approach in tribology.

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