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Research Paper

The effect of transient conditions on synovial fluid protein aggregation lubrication

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ABSTRACT

Little is known about the prevailing lubrication mechanisms in artificial articular joints and the way in which these mechanisms determine implant performance. The authors propose that interfacial film formation is determined by rheological changes local to the contact and is driven by aggregation of synovial fluid proteins within the contact inlet region. A direct relationship between contact film thickness and size of the protein aggregation within the inlet region has been observed.

In this paper the latest experimental observations of the protein aggregation mechanism are presented for conditions which more closely mimic joint kinematics and loading. Lubricant films were measured for a series of bovine calf serum solutions for CoCrMo femoral component sliding against a glass disc. An optical interferometric apparatus was employed to study the effects of transient motion on lubricant film formation. Central film thickness was measured as a function of time for a series of transient entrainment conditions; start-up motion, steady-state and non-steady-state uni-directional sliding, and bi-directional sliding. The size of the inlet aggregations was found to be dependent upon the type of transient condition. Thick protective protein films were observed to build up within the main contact region for all uni-directional tests. In contrast the inlet aggregation was not observed for bi-directional tests. Contact film thickness and wear was found to be directly proportional to the presence of the inlet protein phase. The inlet phase and contact films were found to be fragile when disrupted by surface scratches or subjected to reversal of the sliding direction.

1. Introduction

Articular joint lubrication is one of the most difficult problems in tribology as these implants experience transient loading and kinematics and has a complex biphasic lubricating fluid (Dowson and Neville, 2006). As yet little is known about the prevailing lubrication mechanisms in artificial joints and this presents a potentially serious gap in our knowledge, as these mechanisms determine film formation and hence wear. There is currently a widespread tendency within the literature to confine the tribological mechanisms operating during the gait cycle to a single lubrication regime

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Nomenclature

AA	adduction/abduction
BCS	bovine calf serum
CrCoMo	FS75 chromium, cobalt and molybdenum alloy
CoC	ceramic-on-ceramic
EHL	elastohydrodynamic lubrication
FE	flexion/extension
IOR	inward/outward rotation
LHMoM	large head metal-on-metal
MoM	metal-on-metal
MoP	metal-on-polymer
η	dynamic viscosity
OA	osteoarthritis
PAL	protein aggregation lubrication
R'	reduced radius
s	inlet reservoir length
SAPL	surface active phospholipid
SF	synovial fluid
R_a	arithmetic mean surface roughness
U	entrainment speed
W	applied load

(Smith et al., 2001). The two most popular theories are Boundary and Elasto-Hydrodynamic lubrication which differ significantly in film formation mechanisms, wear characteristics and the response to changing contact conditions (Myant and Cann, 2014). The arguments for (or against) these commonly held ideas were found to be overly simplistic; either ignoring the transient kinematic and loading conditions prevalent in artificial articular joints or the complex rheological and chemical nature of synovial fluid. Classical EHL models are commonly employed to predict film thickness, and hence performance, in artificial hips (Yew et al., 2004). This analysis is based on the flawed assumption that implant lubrication can be described by EHL mechanisms developed for simple Newtonian fluids in steady state conditions (Hamrock and Dowson, 1978).

Recently the authors have suggested a novel lubrication mechanism describing film formation for complex fluids containing proteins (Fan et al., 2011; Myant et al., 2012; Myant and Cann, 2013). The model has been developed entirely from experimental studies of model SF lubrication. One of the key findings is that the lubricant film thickness does not obey EHL rules; i.e. positive speed and negligible load dependency (Myant and Cann, 2014; Stachowiak and Batchelor, 2005). It was concluded that film thickness predictions could not be made using simple Newtonian fluid rheology and steady state contact conditions. Rather, in this model interfacial film formation is determined by rheological changes local to the contact and is driven by aggregation of proteins within the contact inlet region. This concentration of proteins now feeds the contact which a new lubricant phase; which has a greatly increased protein content and viscosity, causing much higher than predicted film thickness (Myant et al., 2012).

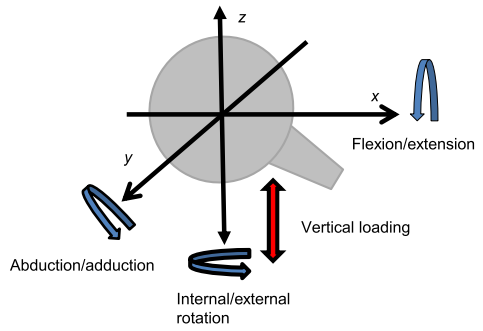

Fig. 1 – Representation of a hip joint showing all three axis of rotation.

Previous results demonstrated a clear correlation between inlet size and contact film thickness (Myant and Cann, 2013). Much of this earlier work studied simple uni-directional sliding contacts; however articular joints actually experience sliding on multiple axes and reversals in the sliding direction. It is likely that this gait like motion will disrupt the proteinacous inlet phase having a significant effect on contact film thickness. The introduction of wear debris or surface scratch may also disrupt lubricant film formation. This paper investigates the effect of inlet disruption on contact film thickness, caused by transient motion and the passage of surface scratches.

1.1. *Background*

Earlier results demonstrated that model SF solutions demonstrate complex time-dependent film thickness behaviour that is not characteristic of a simple Newtonian fluid (Fan et al., 2011). The effect of the deceasing gap height in the inlet region and relative motion of the surfaces (SRR) is to collect proteins at the entry to the contact. These conditions cause a protein enriched phase to form a new inlet reservoir. This process has been observed for similar complex fluids; and is termed bulk phase separation (Stokes et al., 2001). The new protein-gel phase has a much higher viscosity than the bulk solution. Consequently, a significantly thicker film is formed than would be predicted by classical EHL theory, when the bulk rheological properties are employed (Myant and Cann, 2013). The subsequent contact film thickness is controlled by the rheological properties of this new inlet reservoir and not the bulk solution. Contact entry of this protein phase is complex and dependent on operating conditions (speed, load, geometry) and lubricant properties (molecule size, concentration) (Myant et al., 2012). A direct relationship between contact film thickness and the length, and width, of protein aggregation within the inlet region has been observed (Myant and Cann, 2013). Thus we adopted the 'PAL—Protein Aggregation Lubrication' acronym identifying this process.

Our initial work was applied to simple pure sliding unidirectional contacts, which enabled us to determine the fundamental lubrication mechanisms occurring for protein containing fluids. However, in reality an articular joint undergoes complex kinematic and transient loading cycles.