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Lubrication regime of the contact between fat and bone in bovine tissue

P Theobald[1]*, **C Byrne**[1], **S F Oldfield**[2], **D Dowson**[1], **M Benjamin**[2], **C Dent**[1], **N Pugh**[1], and **L D M Nokes**[1]
[1] Institute of Medical Engineering and Medical Physics, Cardiff University, Cardiff, UK
[2] School of Biosciences, Cardiff University, Cardiff, UK

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Abstract: Fat pads are masses of encapsulated adipose tissue located throughout the human body. Whilst a number of studies describe these soft tissues anatomically little is known about their biomechanics, and surgeons may excise them arthroscopically if they hinder visual inspection of the joint or bursa. By measuring the coefficient of friction between, and performing Sommerfeld analysis of, the surfaces approximating the *in vivo* conjuncture, this contact has been shown to have a coefficient of friction of the order of 0.01. The system appears to be lubricated hydrodynamically, thus possibly promoting low levels of wear. It is suggested that one of the functions of fat pads associated with subtendinous bursae and synovial joints is to generate a hydrodynamic lubricating layer between the opposing surfaces.

Keywords: Kager's fat pad, biotribology, synovial fluid, Stribeck, coefficient of friction

1 INTRODUCTION

The coefficient of friction between two mating surfaces is the ratio of the frictional force to the applied load. Three distinct modes of lubrication have previously been identified: boundary, mixed, and fluid film. In boundary lubrication, the coefficient of friction is relatively high (typically about 0.1) with the layer of lubricant covering the conjoining surfaces and being of insufficient thickness to achieve complete surface separation. Thus, wear at the conjuncture is expected. Optimum fluid-film lubrication can yield coefficients of friction as low as 0.001. Synovial fluid typically provides this layer in the synovial joint [**1**, **2**]; thus minimal wear is expected at such a conjuncture. The mixed-lubrication regime has properties between these two extremes.

Previous studies of friction within biological systems have concentrated on studies of natural and total replacement joints [**3–6**]. The former work has revealed the fundamental nature of the remarkable bearing characteristics of healthy natural synovial joints, while the latter has been dedicated to an effort to decrease wear and thus to increase the longevity of prostheses. Related studies have been concerned with efforts to improve the comfort of both clothing [**7**, **8**] and grooming [**9**, **10**]. Despite the need for information regarding *in vivo* surface contacts for improving clinical practice and advancing orthopaedic designs, such studies are limited by difficulties associated with ethical considerations, tissue acquisition, and manufacturing limitations. While extensive studies of synovial joints [**6**, **11**, **12**] have been published, little is known about soft-tissue lubrication [**12**]. There appear to be no previous accounts of the lubrication mechanisms associated with the presence of fat pads both in synovial joints and in subtendinous bursae [**13**].

Fat pads are masses of adipose tissue that have been given relatively little attention by clinicians, although the significance of Hoffa's pad in the knee in association with knee pain is well documented [**14**, **15**]. Some fat pads form compression-resisting devices which may act as effective shock absorbers; others are a prominent feature of synovial joints or subtendinous bursae [**13**]. The former include the heel pad on the plantar surface of the foot which bears approximately 70 per cent of the body weight [**16**] on heel strike and absorbs 90 per cent of the

**Corresponding author: Institute of Medical Engineering and Medical Physics, Cardiff University, Queens Building, The Parade, PO Box 925, Cardiff, CF24 0YF, UK. email: TheobaldPS@cardiff.ac.uk*

energy generated [**17**]. The latter includes Kager's fat pad, situated in Kager's triangle, between the Achilles tendon, flexor hallucis longus, and the calcaneus. Kager's fat pad is a highly mobile structure which protrudes into the retrocalcaneal bursa on plantar flexion [**18**], sliding over the periosteal fibrocartilage covering the calcaneus. As its tip has a synovial membrane that secretes synovial fluid into the bursa, the tribological role of this fat pad is likely to be significant.

The current lack of knowledge of fat pad biomechanics is likely to be a key factor in the decision of many surgeons to excise parts of this tissue if it obscures the arthroscopic view of a synovial joint. Several decades ago, a similar lack of understanding of function led to what is now widely recognized as an inappropriate excision of knee joint menisci [**19**]. Menisci are now known to have important functions as load-bearing surfaces and the current surgical preference is to preserve rather than to remove them. Thus, the purpose of the present study is to highlight the potential importance of fat pads in the lubrication mechanisms of joints and bursae by estimating their coefficient of friction.

2 MATERIALS AND METHODS

The fat pad situated immediately proximal to the phalanges was harvested from four skinned bovine legs, 18 months old and obtained fresh from an abattoir. In addition, synovial fluid was aspirated from the medial and lateral sides of the metacarpophalangeal joint cavities, using a 20 ml gauge syringe and needle. The apparatus, shown diagrammatically in Fig. 1, consisted of an aluminium tube A (wall thickness, 5 mm; outer diameter, 25 mm; length, 300 mm), pivoted and freely rotating on a pillar with specially modified light bearings and suspended over either a glass or a Perspex disc D.

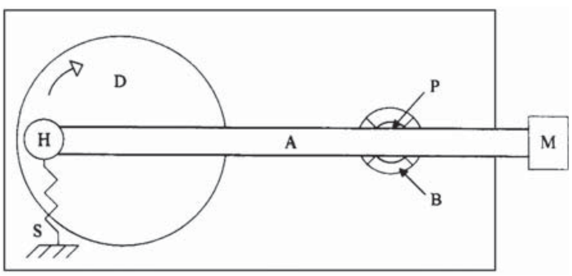

Fig. 1 Diagrammatic representation of the apparatus: A, arm; B, bearing; D, rotating disc; H, specimen holder; M, counterbalance mass; P, pillar; S, spring. The arrows indicate the direction of rotation

This apparatus was successfully validated by comparing the positive gradient of the data points obtained when measuring bovine synovial membrane (Fig. 2) with that achieved by Cooke *et al.* [**12**] (dashed line in Fig. 2) when examining similar tissue. Both indicative of fluid-film lubrication, the slight offset of the results may be caused by a number of factors including the viscosity of the synovial fluid, which can vary four-fold depending upon the health of the joint [**1**]. The fact that the coefficient of friction lies predominantly between 0.001 and 0.01 is further evidence of this lubrication regime, and thus of successful validation [**20**, **21**].

The mean average roughness (R_a) of four measurements (Form Talysurf Series 2, Taylor–Hobson Ltd, UK) of each of the surfaces was calculated. The fat pad was then attached to the specimen holder H at the end of the arm using Dermabond tissue adhesive (Ethicon Inc., USA), before being positioned upon the disc. A counterbalance M ensured zero net loading. Excess synovial fluid was used to lubricate the conjunction between the rotating glass or Perspex disc and the fat pad.

The specimen was vertically loaded against the rotating disc in the range 0.5–10 N. The deflection of the arm promoted by friction between the fat pad and the rotating disc was resisted by a spring S of known stiffness ($k = 0.02$ N/mm). The *in-vivo* speed of movement of Kager's fat pad was measured in four volunteers using dynamic ultrasound during the gait cycle at a gentle cadence. It was estimated as reaching 15 mm/s, and thus the minimum experimental speed that was achievable (16 mm/s) was used throughout the current work. Although the maximum experimental speed (140 mm/s) almost certainly exceeded the fat pad speed during running, predicted to be approximately two and a half times greater than that during gentle cadence, it was nevertheless used to increase the range of test conditions. To ensure that high-quality data were achieved, the disc was ramped up to the desired speed for approximately 10 s, before the arm was allowed to settle. The deflection of the arm was then logged for 10 s, with ten readings per second being recorded on a personal computer via a data logger (Pico Technology Ltd, UK). The mean deflection during the recording period was calculated and recorded. The coefficient of friction was then calculated and the results were plotted against the ratio of sliding speed to load. This ratio is representative of the Sommerfeld number for a given viscosity and geometry. Comparison of the resulting trace against the Stribeck curve (Fig. 3), and the calculated levels of friction against known values,

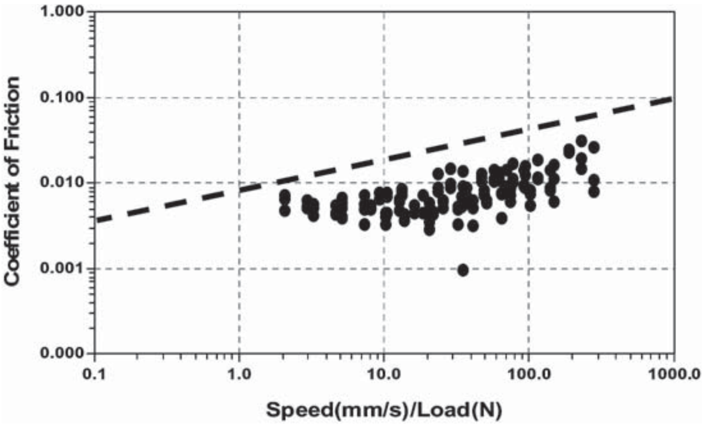

Fig. 2 Variation in the coefficient of friction of bovine synovial membrane against a Perspex disc in the presence of bovine synovial fluid with reduced Sommerfeld number. The apparatus was successfully validated following a comparison of the results with those of Cooke *et al.* [**12**] (dashed line)

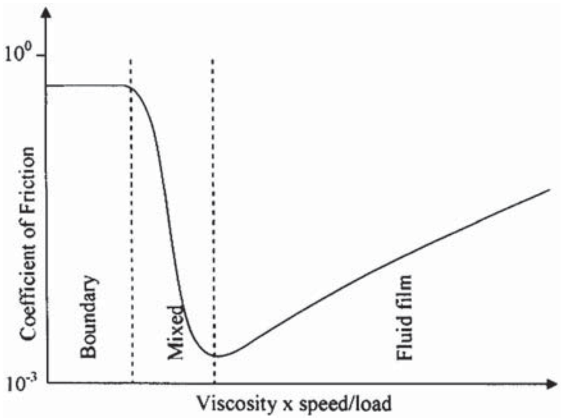

Fig. 3 Representation of the Stribeck diagram relating the coefficient of friction to the Sommerfeld number

enabled the dominant lubrication regime between the fat pad and bone to be determined.

3 RESULTS

The results obtained from the fat pad–rotating disc conjunction are summarized in Figs 4 and 5 for the glass and Perspex discs respectively. These graphs show how the coefficient of friction of the fat pad on the two surfaces depended on the ratio of speed to load and hence upon the Sommerfeld number.

The glass disc results clearly show a positive gradient, indicative of fluid-film lubrication. The Perspex disc results displayed in Fig. 5 exhibit similar levels of friction coefficient to those obtained with the glass disc. However, the rising trend of the coefficient of friction as the Sommerfeld number was reduced in the lower range of values suggests that the conjunction was encountering some mixed lubrication.

4 DISCUSSION

The values of coefficient of friction presented in Figs 3 and 4 are relatively low and representative of fluid-film lubrication conditions. The presence of this mode of lubrication can be supported by considering three different criteria.

1. Comparison of the shapes of the relationships (i.e. the rising trend) between the coefficient of friction and the reduced form of the Sommerfeld number (represented by the ratio of sliding speed to load) with the distinct form of Fig. 2 is indicative of fluid-film lubrication.
2. The majority of the data points lie within the coefficient of friction range 0.001–0.01; it is well recognized that fluid-film lubrication predominates within these boundaries [**12**, **21**].
3. Mixed lubrication is also evident (in particular, in Fig. 5), which occurs when the fluid-film lubrication breaks down at lower speeds and higher loads.

Whilst the well-defined positive gradient obtained for the interaction between fat pad and glass shown in Fig. 4 clearly reflects hydrodynamic lubrication, comparing Fig. 5 with the Stribeck curve indicates that there was a transition from fluid-film to mixed lubrication at lower speeds or higher loads. This characteristic has been reported earlier for synovial joints [**2**, **22–25**]. As the hydrodynamic layer broke down at slower speeds, some surface contact was

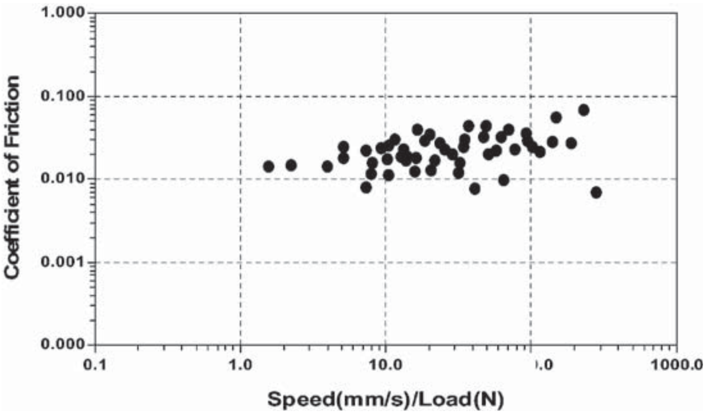

Fig. 4 Variation in the coefficient of friction of bovine fat pads against a glass disc in the presence of bovine synovial fluid with reduced Sommerfeld number

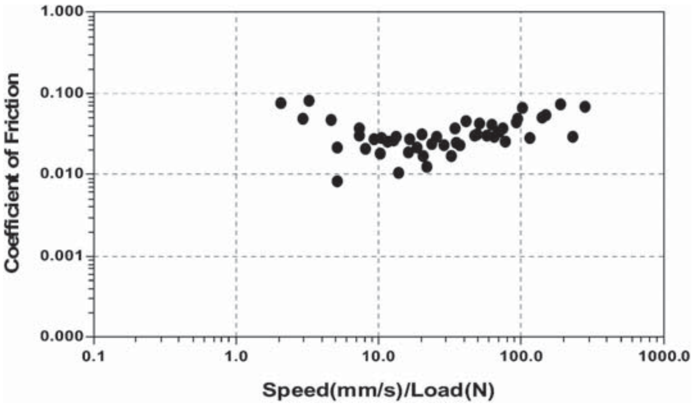

Fig. 5 Variation in the coefficient of friction of bovine fat pads against a Perspex disc in the presence of bovine synovial fluid with reduced Sommerfeld number

expected between opposing asperities, since the surface roughness of the Perspex ($R_a = 0.297$ μm) was greater than that of glass ($R_a = 0.034$ μm). Since similar coefficients of friction were detected between the fat pad and glass and between the fat pad and Perspex, it seems clear that fluid-film lubrication regimes predominated at the contacts with both surfaces. However, it is possible that this mode of lubrication could have developed owing to differences in the fat pad characteristics rather than to the change in the counterface alone [**26**].

The viscosity of the lubricant, synovial fluid, is significant in determining the lubrication regime. In this study it was assumed that the viscosity of the shear thinning lubricant was constant, since little is known about the variation in synovial fluid viscosity with the high shear rates [**2**] likely to have been encountered in these tests.

It is also well known that temperature affects the viscosity of synovial fluid [**1**]. The experiments reported here were conducted under atmospheric laboratory conditions, but no attempt was made to measure the temperature in the lubricated conjunction. The mean laboratory temperature of 18 °C remained reasonably constant and it is therefore unlikely that changes in ambient temperature would have had a significant effect upon the major features of the results. The problems of measuring the viscosity of synovial fluid have been reported by others [**12**, **26**], but it was felt to be inappropriate to include this parameter in the reduced Sommerfeld number adopted in Figs 4 and 5.

Whilst the area of contact at the experimental conjuncture was similar to that *in vivo*, the shape of the tissues did vary. Physiologically, the wedged shape of Kager's fat pad is more likely to encourage the formation of a lubricating layer of synovial fluid than the shapeless bovine fat pad used experimentally. In contrast, the formation of a hydrodynamic film is likely to have been encouraged experimentally by the flatter profile of the disc in comparison with that of the *in vivo* bone geometry. As the magnitude of loading at the physiological conjuncture is unknown, the accuracy of the loading environment applied at the experimental conjuncture is unclear. In addition, whilst the approximation of glass and Perspex to fibrocartilage (the articulating tissue covering the bone) has never been reported, these surfaces have been favourably compared with articular cartilage [**12**, **26**], which is functionally similar. The experiments were carried out under steady rotation of the disc, whilst the more physiologically correct motion is that of reciprocation. No attempt has been made to introduce oscillation into the disc motion at this stage but, in similar experiments on synovial membrane, disc oscillation was reported to be insignificant [**26**]. Consistent experimental conditions were achieved by controlling the extent of arm deflection through adjustment of the spring position.

Since hydrodynamic lubrication appears to operate in relation to bovine fat pads, it is suggested that the fat itself may be influential in maintaining a hydrodynamic film *in vivo*. If the present findings can be extrapolated to human fat, then Kager's fat pad, which protrudes into the synovial fluid-containing retrocalcaneal bursa, may serve to prevent gravity from pooling fluid at the lowest point in the bursa and thus to reduce the risk that the contacting surfaces become dry. Fat pads may play a role analogous to that of menisci in spreading synovial fluid [**19**]. It should be recalled that a 20 per cent increase in friction has been reported within the knee following meniscectomy [**19**, **27**, **28**]. Hence, an understanding of the biomechanical properties of fat pads is important and further studies are planned to explore their frictional and load-bearing characteristics.

5 CONCLUSION

It has been established that both contacts approximating the fat pad–fibrocartilage conjuncture are lubricated hydrodynamically, with a coefficient of friction of about 0.01. These initial results must be viewed with some caution, since they relate to bovine rather than to human fat pads. However, they do suggest that a structure such as Kager's fat pad, which has been shown in previous studies to move in and out of the retrocalcaneal bursa according to foot position [**18**], could play a role analogous to that of the menisci in the knee.

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