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On the Role of Surface Roughness in Ankle Joint Replacements

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Abstract
Research efforts in biomechanics have geared towards the long-term effectiveness and survival of total joint replacements, because of osteoarthritis causes loosening, instability, wear of articulating components and finally loss of function. Surface roughness of articulating components significantly influences their tribological behavior. Other factors affecting the wear of articulating surfaces include material and geometrical properties. In this work, the human ankle joint is represented by an equivalent ellipsoid-on-plane model to study the effect of surface roughness on the pressure profile, film shape, minimum film thickness, lambda ratio (λ) and coefficient of friction in total joint replacements under steady-state conditions. The main purpose here is to promote fluid film lubrication and therefore, reduce wear in ankle joint replacements.

Keywords: *EHL, Surface roughness, film thickness*

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INTRODUCTION

In recent years, total joint replacements for osteoarthritis joints have received considerable attention as an effective alternative. However, these artificial joints suffer from almost unavoidable complications due to loosening, instability and wear of articulating components. This has inspired several researchers to develop new and improved implant designs over the last few decades. The focus of experimental and theoretical research investigations pertaining to biomechanics has shifted to long-term effectiveness and survival of total joint replacements. It is well-known that mathematical modeling of a synovial joint problem serves not only to predict the performance parameters, which are difficult to measure experimentally, but also to simulate the system behavior under varying physiological conditions. The wear of articulating components—one of the major causes of synovial joint failure—can be reduced significantly by improving the lubrication characteristics. Therefore, lubrication modeling is an effective tool employed in research projects aimed at enhancing the clinical performance and life expectancy of artificial human joints.

Most of the theoretical studies pertaining to artificial human joints focus on hip and knee joints. As a comprehensive review of the subject matter is beyond the scope of this paper, some of the pertinent papers are cited in the following text. Goenka formulated and solved Reynolds equation in spherical coordinates by means of finite element approach [1]. This work established the basis to investigate lubrication of soft-on-hard couples with a realistic ball-in-socket scheme. Kothari et al. and Cheng et al. studied the influence of nonspherical bearing surfaces under steady-state conditions [2, 3]. In a later work, Jin and Dowson presented a full transient hydrodynamic lubrication analysis using more realistic working conditions [4].

Wang and Jin investigated the effects of the cup inclination angle and the combined flexion–extension and internal–external rotation on the lubrication characteristics pertaining to artificial hip joints [5]. Jalali-Vahid et al. employed elastohydrodynamic lubrication (EHL) model for ball-in-socket configuration to predict the lubricant film thickness in natural and artificial hip joints [6–9]. Moreover, numerical simulations carried out for ball-in-socket and ball-on-plane configurations yielded quasi-identical results [10, 11]. Like hip implants, considerable studies are available in literature for knee joint conjunctions. For instance, Murakami et al. presented the fluid film formulation in a knee joint under walking conditions [12]. Mongkolwongrojn et al. analyzed the transient fluid film behavior in artificial knee joints based on EHL point contact simulations with non-Newtonian fluid model [13]. The importance of joint conjunction in knee prostheses undersimulated walking conditions was highlighted by Jin et al. and Su et al. using lubrication analyses based on ellipsoid-on-plane model [14, 15]. As far as the ankle joint conjunction is concerned it has generally been represented as a line contact instead of point contact model [16–18].

Since EHL point contact simulations involves a host of challenges including numerical instabilities, slow rates of convergence, heavy computational effort and memory storage requirements. While all these implants have similar articulating materials, surface roughness and lubricant properties, there are marked differences in the implant geometries as well as in the motion and the load experienced. These factors are expected to alter the wear characteristics of different implants significantly. Therefore, the variables which are considered critical in the wear of hip and knee joints should be re-assessed for the case of ankle joints.

In addition, most of the earlier theoretical studies on artificial human joints assumed the lubricant to be Newtonian; however, the synovial fluid is known to exhibit non-Newtonian behavior [19]. In particular, its viscosity is lower at higher shear rates; i.e., it exhibits shear thinning behavior [24–41]. Another important aspect which needs due consideration in EHL analysis of artificial joints pertains to surface roughness as it may significantly influence the wear rate. In the present work, the human ankle joint is represented by an equivalent ellipsoid-on-plane model so as to investigate its EHL behavior with due consideration to the effect of surface roughness on pressure profile, film shape, minimum film thickness, λ ratio and coefficient of friction. The analysis is carried out under steady state conditions as it has often been affirmed that the transient film thickness does not vary much over the normal walking cycle and the average load and entrainment velocity yield film thickness values quite close to that found in transient analysis [8, 20–22]. The main purpose of present work is to promote fluid film lubrication and therefore, reduce wear in ankle joint replacements.

SIMULATION RESULTS

The present EHL analysis involves the simultaneous solution of Reynolds, film thickness and load balance equations using a modified Newton-Raphson algorithm. The governing equations are discretized using finite difference scheme. These governing equations are solved using the procedure outlined by Katyal and Kumar to evaluate the EHL characteristics in terms of λ ratio pertaining to ankle contact joint replacements [23]. The solution domain in the present simulations ranges from $X = -3.0$ to 1.5 and $Y = -1.8$ to 1.8 with a uniform mesh of 501 × 501 points. It has been verified that further mesh refinement causes negligible change in the results. The principal results from this work are presented in the following section.

Lubrication Regime Analysis

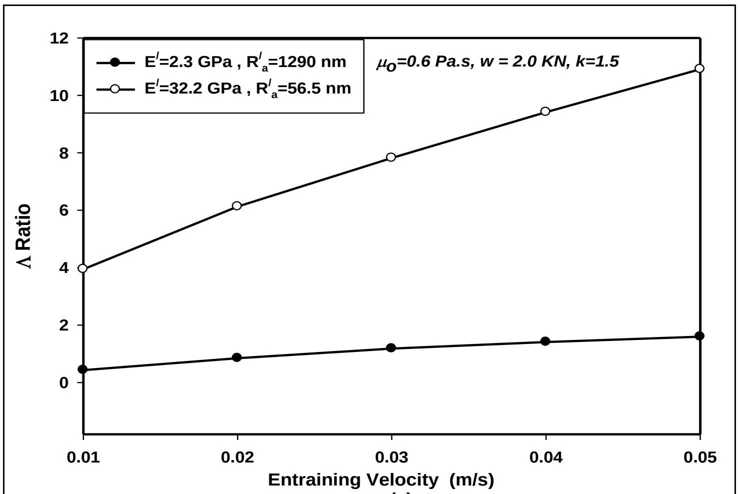
The long-term performance and success of joint replacements depend on the mode of lubrication between the contacting surfaces. Moreover, the effective roughness of the articulating surfaces determines the lubrication regimes in these joints. The main purpose under this section is to investigate the role of the lambda (λ) ratio under various combinations of material, geometrical and lubricant properties. In case of artificial joints, the lubrication is dependent on lubricant viscosity, sliding speed and surface roughness between the articulating surfaces in contact. Figures 1 and 2 show the variation of λ ratio results plotted against entraining velocity with various combinations of operating and design parameters. Figure 1 corresponds to conventional and advanced material combinations while Figure 2 relates to soft layer bearing joints. For Figure 1, the various parameters include the effects of elastic modulus, lubricant viscosity, ellipticity and applied load between the articulating surfaces in contact while Figure 2 relates to soft layer bearing joints, which include the effect of soft layer modulus and soft layer thickness. It should be noted that no comparisons with experimental data are presented here, because no film thickness measurements from actual ankle joint simulators seem to be available in the literature.

Figure 1(a) shows the variation of λ ratio against entraining velocity with different elastic modulus (2.3 and 32.2 GPa). It can be clearly seen here that with the increase in the entraining velocity, λ ratio increases for all the material combinations chosen in the present study. For a given entraining velocity, a decrease of the elastic modulus of the bearing material from $E^{/}$=32.2 GPa to $E^{/}$=2.3 GPa results in an increase of the minimum film thickness values. Moreover, compound surface roughness values also increases from $E^{/}$=32.2 GPa to $E^{/}$=2.3 GPa combinations, which leads to overall decrease of λ ratios.

Thus, it is clear from Figure 1(a) that depending on the value of the entraining velocity and elastic modulus, the lubrication regimen moves from boundary to full-film lubrication. With the increase of lubricant viscosity from μ_0 = 0.06 to 1.0 Pas resulted in a significant increase in minimum film thickness, which in turn leads to increase of the λ ratio values as shown in Figure 1(b). Thus, clearly depending on the value of the entraining velocity and lubricant viscosity, the lubrication regimen shifts from boundary lubrication to full-film lubrication.

Figure 1(c) shows the influence of load and entraining velocity on λ ratio values. Clearly, increase in the applied load results in a decrease of the λ ratio values. This is because with the increase in the applied load, both the film pressure and contact area increase significantly, which leads to decrease in minimum film thickness values and hence λ ratio values.

The effects of ellipticity ratio and entraining velocity on the λ ratio values are shown in Figures 1(d). It can be observed that the λ ratio increases considerably as the ellipticity ratio and entraining velocity increases. Since, with the increase of ellipticity ratio from k =0.5 to 5, approaching line contact, minimum film thickness and hence λ ratio increases significantly. For soft layer bearing joints as shown in Figure 2, the highest λ ratio can be achieved by decreasing the modulus and increasing the thickness of the soft layer material. These simulations thus appear to offer support that mixed and fluid-film lubrication can be expected in ankle joint replacements. These result simulations will be helpful in specifying the various pairs of combinations required to achieve particular lambda ratio values, which in turn will enhance the clinical performance and life expectancy of artificial human joints.



(a)

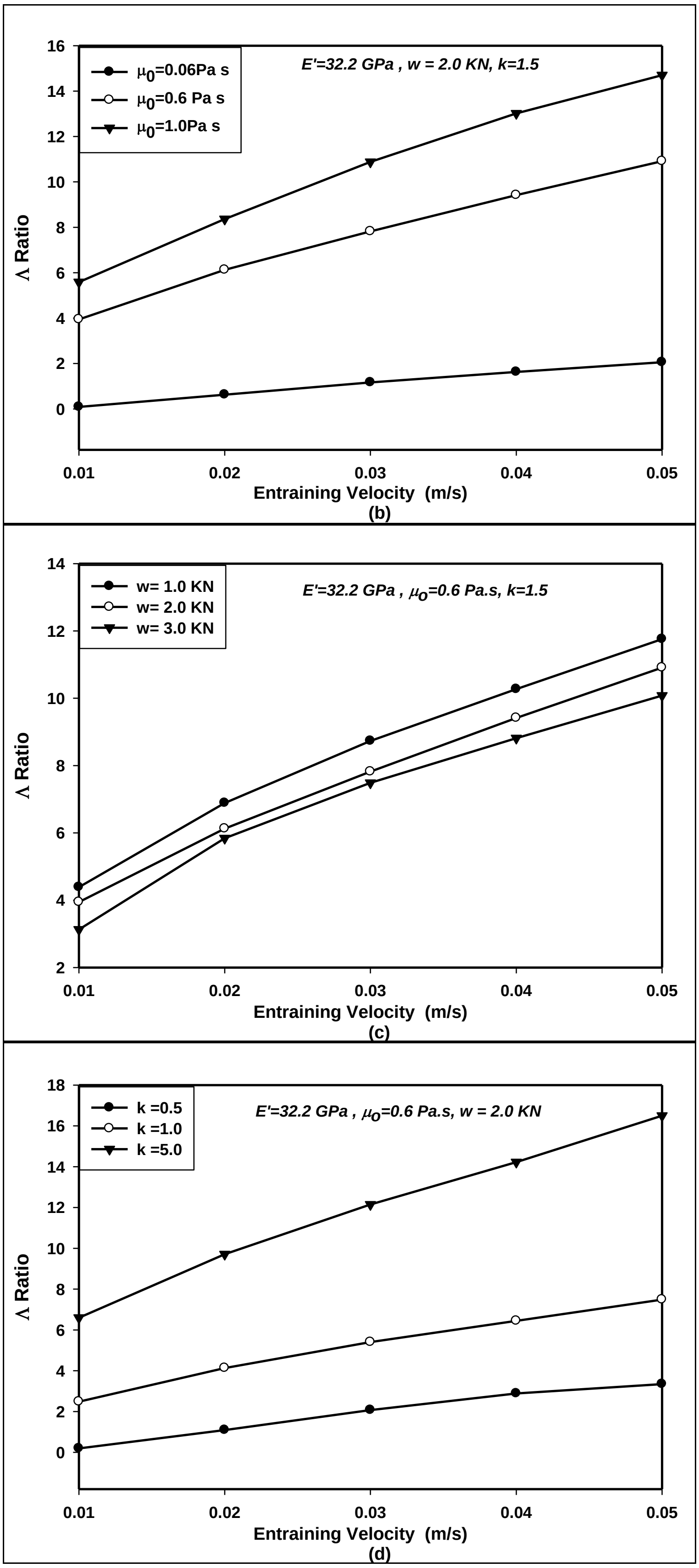


Fig. 1: *Predictions of the λ Ratio against Entraining Velocity for Ankle Joint Replacement with A' = 0.1 and* $\overline{\lambda}$ *= 0.25: (a) Influence of Apparent Viscosity; (b) Influence of Equivalent Elastic Modulus; (c) Influence of Applied Load and (d) Influence of Ellipticity Ratio.*

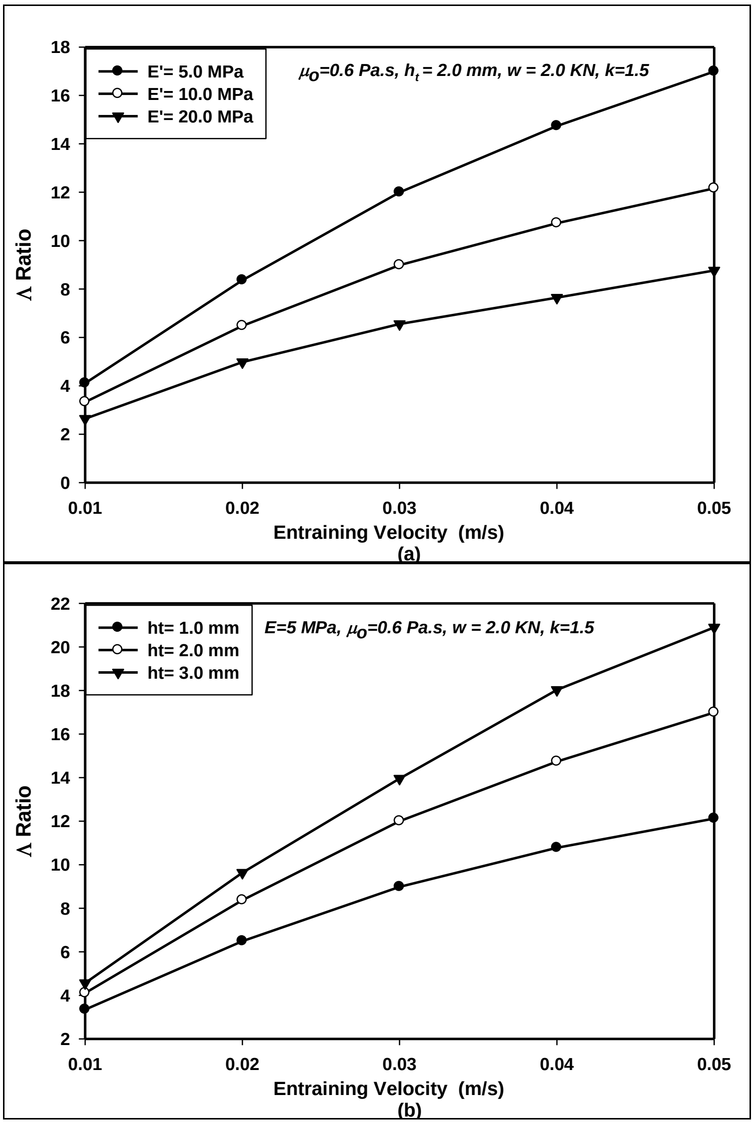


Fig. 2: *Predictions of the λ Ratio against Entraining Velocity for Ankle Joint Replacements: (a) Effect of Soft Layer Young's Modulus; (b) Effect of Soft Layer Thickness.*

DISCUSSIONS

This analysis takes into account the surface roughness effects as it produces significant variation in the pressures generated in the fluid film, shape of the fluid film, minimum film thickness, lambda ratio and coefficient of friction. The effect of surface roughness on the minimum film thickness can be determined in terms of roughness correction factor (C_R) which can be utilized in the design stages. These results suggest that manufacturing process parameters should be carefully controlled so as to eliminate not only high amplitude but also short wavelength components of surface topography because they play an important role in deciding the tribological behavior of the contacting surfaces. It should be noted that the main purpose of the present analysis is to investigate how the fluid film formulation in ankle joints can best be achieved. Boundary or mixed lubrication is the predominant lubrication regime that operates in artificial joints that have a hard-on-soft bearing surfaces which can have negative consequences due to higher friction and wear. In the work reported here, the various pairs of material combinations (Titanium or CoCrMo alloy against UHMWPE, Pyrocarbon on Pyrocarbon and CoCr alloy on Polyurethane) have used to examine the predicted lubrication regimes in ankle joint conjunctions. From the EHL simulations, it has shown that predicted lambda ratio can be enhanced by increasing the entraining velocity, decreasing the applied load and increasing the ellipticity ratio between the articulating surfaces. But the predominant lubrication regime that operates for all parameter combinations in ankle joint replacements is boundary or mixed.

Other material combination (Pyrocarbon on Pyrocarbon) that have been used or suggested for metacarpophalangeal prostheses [43, 44], that could potentially be used as bearing material for ankle joint replacements is also considered in this study. Pyrocarbon is a popular material used for the implants and can mimic the normal functions of the joint. It exhibits exceptional wear performance against bone compared to ceramic and metals. It has modulus of elasticity similar to cortical bone minimizing stress shielding effects and resorption. The long-term clinical experience with Pyrocarbon exceeds 40 years as heart valve prosthesis and 30 years as orthopedic implants. Regarding the Pyrocarbon-on-Pyrocarbon material combination, the presented results show that ankle joint can predominately operate in the mixed or fluid film lubrication regime.

Moreover, compliant layer technology potentially offers an alternative bearing to conventional joints and may give longevity. In the present work, soft layered ankle joints have also been proposed. Based on the results for all the material combinations under given design and operating conditions, it is found that metal-on-polymer (Titanium or CoCrMo alloy against UHMWPE) pairs are expected to function in the boundary or mixed lubrication, while the Pyrocarbon-on-Pyrocarbon and CoCr-on-Polyurethane combination offered the potential of full-film lubrication. Thus, the present work shows that the use of CoCr-on-Polyurethane and Pyrocarbon on Pyrocarbon material combinations may help in improving the lubrication regime between the bearing surfaces, which will lead to lower wear.

The findings of this part of the study propose the application of the elastomer and pyrocarbon materials in these joint replacements. Furthermore, the load and entraining velocity are operating parameters, while the ellipticity ratio and the elastic modulus of the bearing materials are design parameters. The operating parameters cannot be controlled, but the design parameters can be chosen during design to enhance the film thickness. Besides these operating and design parameters the predicted lambda ratio also depends on compound surface roughness values of the contacting surfaces as discussed earlier. Thus, lubrication modeling of ankle joint replacements becomes important, not only to assess the lubrication regime but also to identify design and manufacturing parameters to promote fluid film lubrication in these artificial joints. These results will be helpful for the bio-engineers in determining the performance and long-term success of man-made bearings and specifying the various pairs of combinations required to achieve a particular lambda ratio values.

CONCLUSIONS

Depending on the value of the entraining velocity, elastic modulus, lubricant viscosity, applied load and ellipticity ratio; the lubrication regimen moves from boundary to full-film lubrication. It is found from the simulation results that the metal-on-polymer (Titanium or CoCrMo alloy against UHMWPE) combinations are expected to function in the boundary or mixed lubrication, while the Pyrocarbon-on-Pyrocarbon and CoCr-on-Polyurethane combinations offered the potential of full-film lubrication, which will help the bio-engineers to enhance the clinical performance and life expectancy of ankle joint replacements.

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