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Regression models to predict the behavior of the coefficient of friction of AISI 316L on UHMWPE under ISO 14243-3 conditions

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ABSTRACT

Friction is the natural response of all tribosystems. In a total knee replacement (TKR) prosthetic device, its measurement is hindered by the complex geometry of its integrating parts and that of the testing simulation rig operating under the ISO 14243-3:2014 standard. To develop prediction models of the coefficient of friction (*COF*) between AISI 316L steel and ultra-high molecular weight polyethylene (UHMWPE) lubricated with fetal bovine serum dilutions, the arthrokinematics and loading conditions prescribed by the ISO 142433: 2014 standard were translated to a simpler geometrical setup, via Hertz contact theory. Tribological testing proceeded by loading a stainless steel AISI 316L ball against the surface of a UHMWPE disk, with the test fluid at 37 °C. The method has been applied to study the behavior of the *COF* during a whole walking cycle. On the other hand, the role of protein aggregation phenomena as a lubrication mechanism has been extensively studied in hip joint replacements but little explored for the operating conditions of a TKR. Lubricant testing fluids were prepared with fetal bovine serum (FBS) dilutions having protein mass concentrations of 5, 10, 20 and 36 g/L. The results were contrasted against deionized, sterilized water. The results indicate that even at protein concentration as low as 5 g/L, protein aggregation phenomena play an important role in the lubrication of the metal-on-polymer tribopair. The regression models of the *COF* developed herein are available for numerical simulations of the tribological behavior of the aforementioned tribosystem. In this case, surface stress rather than film thickness should be considered.

1. Introduction

Lubrication theories have been applied for over half a century to explain lubrication mechanisms in synovial joints, both natural and artificial (Dowson, 1966, 2006; Unsworth, 1991; Dowson and Jin, 1992; Li, Guo and Wong, 2016). In particular, specific effects of synovial fluid chemistry and rheology related to the strong interactions of proteins with surfaces, as well as positive cooperative and aggregation phenomena (Malmsten, 1998; Gray, 2004; Oates et al., 2006; Karuppiah et al., 2006; Fang et al., 2009; Rabe, Verdes and Seeger, 2011), have been the subject of extensive experimental research under the loading and arthrokinematics conditions of hip-joint replacements, using optical techniques to observe the behavior of lubricating films thickness (Heuberger et al., 2005; Fan et al., 2011; Mavraki and Cann, 2011; Vrbka et al., 2012; Myant et al., 2012; Myant and Cann, 2013, 2014a, 2014b; Parkes et al., 2015; Necăs et al., 2016). Under the said conditions, it has been determined that film thickness is larger than those contemplated for conventional full-film lubrication models, and that a high-viscosity, gel-like phase is formed at the inlet of the contact (Myant and Cann, 2013, 2014a, 2014b; Necăs et al., 2016). Indubitably, the reported increment in film thickness and viscosity should reflect upon the behavior of the *COF*, the natural response parameter of all tribosystems.

Likewise, lubrication in a total knee replacement (TKR) has been approached both experimentally and numerically from the perspective of elastohydrodynamic lubrication (EHL) theory (Murakami and Ohtsuki, 1987; Jin et al., 1998; Pascau et al., 2009; Mongkolwongrojn, Wongseedakaew and Kennedy, 2010; Su et al., 2011; Kennedy et al., 2013). On a seminal work, Murakami and Ohtsuki (1987) experimentally investigated the formation of lubricating films in knee prostheses under walking conditions, using a knee joint simulator and silicon oils of different viscosity as lubricants. For a polyethylene tibial component, they observed a slight separation between tibial and femoral components immediately after initial contact –formerly known as heel strike

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(Uustal and Baerga, 2004), that decreased along the stance phase, generally becoming a minimum during preswing. During the swing phase, the separation of tibial and femoral components is complete from about 70 to 95% of the walking cycle or stride (Uustal and Baerga, 2004). These experimental results were confirmed numerically. Based on EHL theory and film thickness observations of Murakami and Ohtsuki (1987), Jin et al. (1998) performed a numerical simulation of transient lubrication film-thickness in knee prosthesis to evince the relevance of contact features – conformity, area, and conjunction – in determining fluid film generation. They modeled entrainment and squeeze-film actions assuming a Newtonian, isoviscous, incompressible lubricant. On the subject of contact conformity, Pascau et al. (2009) investigated the effect of prosthetic-joint conformity in the lubrication mechanisms occurring during the stance phase of the stride, using a simplified piecewise linear Cross model to mimic the rheology of the synovial fluid and the walking cycle model by Sathasivam and Walker (1999). Their numerical model considered hydrodynamic lubrication only. They concluded on the importance of this lubrication mode at the beginning of the stance phase, where, coupled with high conformity, it helps to reduce compressive stresses on the polyethylene, significantly. Mongkolwongrojn, Wongseedakaew and Kennedy (2010) explored transient EHL, for point contact, in artificial knee joints using the same loading and velocity cycles of Murakami and Ohtsuki (1987), together with a non-Newtonian Carreau fluid model. They showed the relationship between film thickness and elastic properties of the polymer implant, lubricant viscosity, applied load, and arthrokinematics. Within the scope of their model, they concluded that the minimum film thickness diminishes to its lowest value at toe-off, and argue for a squeeze film effect that helps prevent the film thickness from going to zero at zero velocity. In addition, they observed that, under similar load and velocity conditions, the minimum film thickness is lower for a non-Newtonian fluid than for a Newtonian, adducing this fact to shear thinning effects. Su et al. (2011) developed a time-dependent EHL analysis of a TKR under walking conditions, using an equivalent ellipsoid-on-plane model to represent the contact. Their results show that the central film thickness tends to decrease in the stance phase, but keeps a relatively larger value at the swing phase. Finally, Kennedy et al. (2013) applied the model by Mongkolwongrojn, Wongseedakaew and Kennedy (2010) to the loading and arthrokinematics conditions of the ISO 14243-3 standard, assuming the lubricant fluid to be Newtonian. In this work, they concluded that mixed and boundary lubrication regimes dominate along the walking cycle. It is worth remarking that only the work by Kennedy et al. (2013) followed a standardized procedure.

Mathematical models for lubrication in a TKR rely on the definition of suitable viscosity functions that represent the non-Newtonian nature of the synovial fluids used for in vitro testing, like bovine serum (BS). To this respect, it is very unlikely that the rheology of synovial fluids remains the same under the complex, transient arthrokinematics and loading conditions in a TKR than under rheometry; particularly, the protein aggregation effects, which have been observed to be very sensitive to loading conditions and surface kinematics.

The arthrokinematics of the NexGen® CR-Flex Zimmer® fixed-bearing, left knee-prosthesis model considered by Barceinas-Sanchez et al. (2017) takes place predominantly in the sliding mode, according to the ISO 14243-3:2014 standard (ISO, 2014). It is only during the transition from stance to swing, and at the end of swinging, that a combination of rolling and sliding happens. In this case, sliding speed reaches almost 200 mm/s, at about 85% of the walking cycle, and 150 mm/s, at about 50% of it; also, extremal speed values exist at about 5% and 25% of the cycle – approximately 113 and 64 mm/s, respectively. All of these are higher than the values used for observing film thickness in hip-joint replacement conditions, as summarized by Myant and Cann (2014a) and Necǎs et al. (2016). Nonetheless, by contrasting the tribological behavior of synovial fluid versus that of water, it should be possible to obtain some insight into protein-mediated lubrication mechanisms in a TKR for a stride. In this work, the authors hypothesize that the behavior observed in the *COF* by Barceinas-Sanchez et al. (2017) for a specific model of TKR, under ISO 14243-3:2014 conditions, can be explained, in general terms, by observing the effects of protein adhesion and accumulation on the *COF*, as a function of protein concentration. The expediency of the method herein lays in the fact that there is no restriction as to the use of UHMWPE as a counterpart; in contrast, optical interferometry, which is considered the most accurate experimental technique to measure film thickness (Lugt and Morales-Espejel, 2011), requires the use of a transparent disk, disqualifying the use of UHMWPE in the tribosystem. By removing this limitation, the loads established in the said standard can be fully applied beyond what is usually termed *representative* or *clinically relevant* conditions. Also, in the experimental setup presented here the contact area is completely immersed in the lubricant fluid, eliminating the possibility of fluid flow-related artifacts.

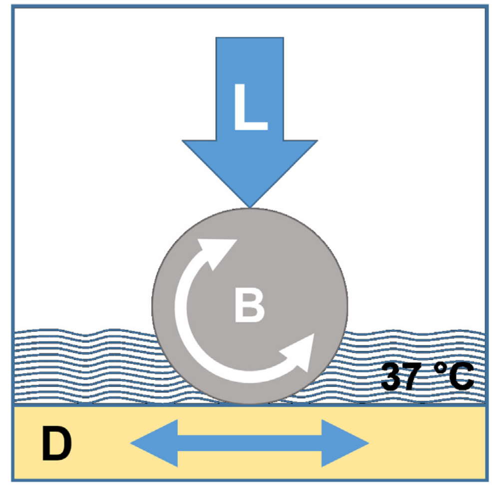

Fig. 1. Schematic representation of the experimental setup. Sliding, rolling and mixtures of both can be achieved by independently driving the loaded ball (B) and the disk (D). The contact area is completely immersed in lubricant at 37 °C.

2. Materials and methods

2.1. Experimental setup

In the experimental apparatus – described elsewhere (Barceinas-Sanchez et al., 2017) – a stainless steel AISI 316L ball loaded against the face of an UHMWPE disk is driven independently from it, in direct or reverse motion, as shown schematically in Fig. 1, to create a variety of motion conditions: from rolling to sliding, and a mixture of both in between. The sliding-to-rolling ratio *SRR* is defined as $|V_r/V_m|$, where $V_r = V_1 - V_2$ is the sliding velocity, and $V_m = (V_1 + V_2)/2$ is the entrainment velocity; V_1 and V_2 are the velocities of disk and ball at the contact point. The tribopair consists of a 19.05 mm diameter stainless steel AISI 316 L ball grade 100, with nominal roughness less than 0.012 µm, and a UHMWPE disk of 46 mm diameter and 6.00 ± 0.02 mm thickness.

The standard test method prescribed in ISO 14243–3:2014 is used in the wear testing of UHMWPE in whole TKR systems when using machines equipped with controls for axial load, flexion-extension (FE) angular motion, anterior-posterior (AP) displacement and tibial