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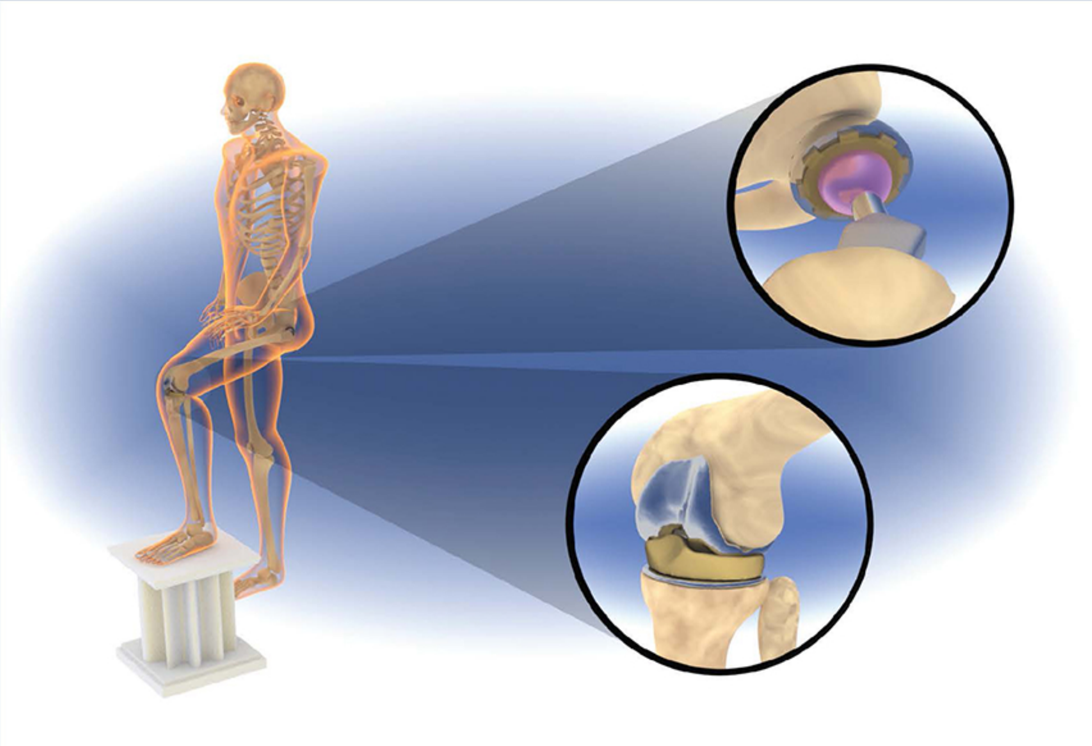

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Preface

Biotribology includes tribological phenomena of natural and implant surface interactions under relative motion in human body. With the theme of "Emerging Technologies and Applications in Biotribology," this book disseminates ideas and research trends in the field of Biotribology. The aim of the book is to present pioneering recent research advances impacting the field of Biotribology. The book focuses on the role of mathematics, chemistry, physics, materials and mechanical engineering on the recent advancements and developments in Biotribology. The scope of the book includes recent developments and future outlooks to the emerging technologies and applications in Biotribology. The state of the art and future technological developments impacting Biotribology are provided. An overview of the recent developments in Biotribology in the areas of lubrication characteristics of artificial joints, biotribological characteristics of textured surfaces, and tribological characteristics of implants are also presented. The book chapters discuss tribological design, mechanisms and characterizations of artificial joints, computational and multibody biomechanical modeling, tribological characteristics, wear analysis and tribocorrosion behavior of metallic implants. The challenges and opportunities for Biotribology are discussed. Biotribology is an important growing field, and topics covered in the book are of great interest to the international tribology community.

Editors

Dr. T. V. V. L. N. Rao received his PhD in Tribology of Fluid Film Bearings from the Indian Institute of Technology Delhi in 2000, and MTech in Mechanical Manufacturing Technology from the National Institute of Technology (formerly known as Regional Engineering College) Calicut in 1994. Rao's current research interests are in Bearings, Lubrication, and Tribology. He has authored (and co-authored) over 120 publications to date. He has secured (as PI and Co-PI) several research grants from the Ministry of Higher Education, Malaysia and a research grant from The Sumitomo Foundation, Japan. Rao is a member of the editorial board (2022) of *Tribology & Lubrication Technology* (TLT). He is a guest associate editor for the *Journal of Engineering Tribology*, *Industrial Lubrication and Tribology*, *Tribology – Materials, Surfaces & Interfaces*, and the *Arabian Journal for Science and Engineering*. Rao is an executive member (2015–2021) of the Malaysian Tribology Society. He is a member of the Society of Tribologists and Lubrication Engineers, Malaysian Tribology Society, and Tribology Society of India. Rao is currently professor in the Department of Mechanical Engineering at Madanapalle Institute of Technology & Science. Prior to joining MITS, he served as research associate professor at SRMIST (2017–2020), visiting faculty at LNMIIT (2016–2017), associate professor at Universiti Teknologi PETRONAS (2010–2016), and assistant professor in BITS Pilani at Pilani (2000–2004, 2007–2010) and Dubai (2004–2007) campuses.

Prof. Dr. Salmiah Binti Kasolang is currently the rector of Universiti Teknologi MARA (UiTM) Pulau Pinang Branch. Her research interest is in Tribology, and specifically hydrodynamic lubrication. She graduated from the University of Wisconsin-Madison in 1992 and later pursued her master's degree in Manufacturing System Engineering at Universiti Putra Malaysia UPM. She did her PhD in the University of Sheffield under the supervision of Prof. Rob Dwyer-Joyce. She has an administrative experience of 10 years as the deputy dean (7 years from 2009 to 2015) and dean (3 years from 2015 to 2017) at Universiti Teknologi MARA (UiTM). She is actively leading a Tribology research group in UiTM with more than 100 indexed publications. Her engagement with MYTRIBOS has enabled her to connect with other tribologists in Malaysia. Currently, she is the president of the Malaysian Tribology Society (MYTRIBOS). She is also the president of President of Society of Mechanical Engineering Liveliness SOMEL, which promotes many aspects of engineering including but not limited to education, research, industry-community engagement, engineering art, and engineering lifestyle.

Dr. Xie Guoxin received his doctoral degree at Tsinghua University, China in 2010, majoring in Mechanical Engineering. After that, he spent two years at State Key Laboratory of Tribology, Tsinghua University, China for postdoctoral research. From 2012 to 2014, he worked at Royal Institute of Technology, Sweden, for another two years' postdoctoral research. Since 2014, he has worked at Tsinghua University as a tenure associate professor. His research interests include solid lubrication, electric contact lubrication, thin film lubrication, etc. He has published more than 80 referred papers in international journals. He won several important academic awards, such as Chinese Thousands of Young Talents, the Excellent Doctoral Dissertation Award of China, and Ragnar Holm Plaque from KTH, Sweden. He is currently an associate editor of *Friction*, and he will be the director of Young Committee of Chinese Tribology Institution.

Dr. Jitendra Kumar Katiyar is presently working as a Research Assistant Professor, in Department of Mechanical Engineering, SRM Institute of Science and Technology Kattankulathur Chennai, India. His research interests include tribology of carbon materials, polymer composites, self-lubricating polymers, lubrication tribology, modern manufacturing techniques and coatings for advanced technologies. He obtained his bachelor's degree from UPTU Lucknow, graduating with Honors in 2007. He obtained his master's from the Indian Institute of Technology Kanpur, India in 2010 and a PhD from the same institution in 2017. He is the life member of Tribology Society of India, Malaysian Society of Tribology, Institute of Engineers, India, and The Indian Society for Technical Education (ISTE) etc. He has authored/co-authored/published more than 25 articles in reputed journals, 30+ articles in international/national conferences, 12+ book chapters, two books published such as, *Automotive Tribology and Tribology in Materials and Application* (Springer) and *Engineering Thermodynamics* for UG level (Khanna Publications). He has served as a guest editor for a special issue of *Tribology Materials, Surfaces and Interfaces*, *Journal of Engineering Tribology Part J*, *Arabian Journal for Science and Engineering*, and the *Industrial Lubrication and Tribology*. He is also an active reviewer in various reputed journals related to materials and tribology. He has delivered more than 30+ invited talks on various research fields related to tribology, composite materials, surface engineering, and machining. He has received research grants from various government organizations such as MHRD, SERB. He has also organized 5+ FDP/short-term courses in tribology and the International Tribology Research Symposium.

AP Dr. Ahmad Majdi Abdul Rani received his PhD in Mechanical & Manufacturing Engineering from Loughborough University, UK, MSc in Industrial Engineering and a BSc in Manufacturing from Northern Illinois University, USA. His research interests are in BioMedical Engineering, Mechanical & Manufacturing Engineering and Tribology. He has supervised and currently supervising more than 20 postgraduate (PhD and MSc) students. He recently received the Leadership in Innovation Fellowship – Newton Award, UK. He has secured three patents and won more than 15 gold awards in exhibitions such as ITEX, MaGRIs (MOSTI), MARS, PENCIPTA, IME, SPDEC, CoRIC, etc. He has authored over 150 publications to date. He has secured (as PI and Co-PI) several research grants from the Ministry of Higher Education, Malaysia (FRGS, PRGS, ERGS, MyBrain) and Universiti Teknologi PETRONAS (YUTP, I-GEN, STIRF). He has been associated with the Department of Mechanical Engineering at Universiti Teknologi PETRONAS since 1998. He has been head of the Department of Mechanical Engineering at Universiti Teknologi PETRONAS from 2009 to 2011.

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1 Recent Developments in Biotribology

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CONTENTS

1.1 INTRODUCTION

Biotribology covers all characteristics of tribology involved with biological systems. The biotribological characteristics cover a widespread range of tribological mechanisms recognized from biological systems which offer important perceptions of

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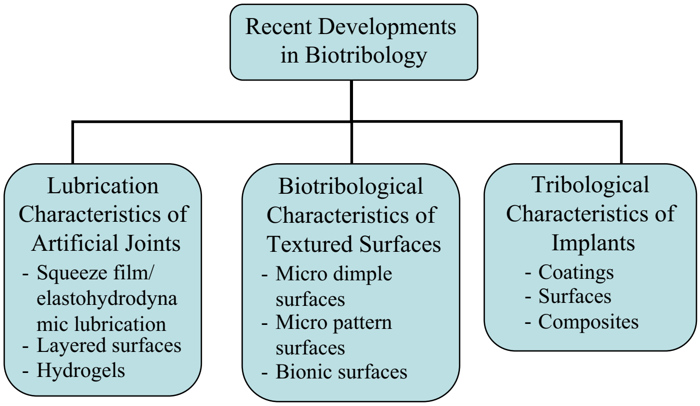

FIGURE 1.1 An overview of recent developments in biotribology.

means and methods for developing biotribology research. The most exclusive and vital concerns in biological systems deal with the medical interventions to be employed for combating diseases to make an influence on enhancement in quality of life. The fundamental theories, design and fabrications have been undertaken driven by the enhancement of life quality and stimulated by natural biological and tribological systems [1]. The natural association particularly develops between tribology, mechanics, and biology because many biological systems rely on adhesion, lubrication, and motion [2].

An overview of the recent developments in biotribology presented in Figure 1.1 is in the areas of: lubrication characteristics of artificial joints, biotribological characteristics of textured surfaces, and tribological characteristics of implants.

1.2 LUBRICATION CHARACTERISTICS OF ARTIFICIAL JOINTS

The squeeze film and elastohydrodynamic lubrication of bearing surfaces play a dominant role in the complex lubrication of artificial joints. There is an emphasis on the efficient numerical tools to predict the lubricant film considering the bearing surface geometry and deformation of artificial hip joints. The importance of lubricant film prediction is further enriched with the transient elastohydrodynamic lubrication process considering the bearing surface geometry and deformation of artificial hip joints [3]. It has been observed that there is an extremely efficient friction reducing effect in synovial joints arising from the presence of charged macromolecules (brush-like) at the superficial lubricated zone of synovial cartilage surface [4]. The coefficient of friction response of lubricated cartilage surface with interstitial synovial fluid pressurization is lower for potentially higher load under steady or transient mechanisms [5]. The investigations on friction-reducing behavior of synovial joints reveal that the boundary lubrication play a major role in contributing to the superior tribological properties of the cartilage surface. The lubricating properties of the synovial fluid, the chemical properties of the surface as well as the mechanical properties of the surface/structure contribute to the friction reducing behavior between the sliding surfaces [6]. The geometric and material parameters of implants facilitate in the progress of lubrication and wear models for extended life and superior performance of synovial joints [7].

TABLE 1.1
Recent Developments in Lubrication Characteristics of Artificial Joints

Lubrication Characteristics of Artificial Joints	Authors
Emphasized the need of efficient numerical tools to solve complex artificial hip joints lubrication	Jin [3]
Highlighted the synovial joints cartilage surface lubrication models	Klein [4]
Emphasis on the cartilage surface interstitial synovial fluid pressurization	Ateshian [5]
Investigated synovial joints cartilage surface boundary lubrication	Crockett [6]
Explored lubrication and wear models of hip implants for extended life and superior performance	Mattei et al. [7]
Examined the synovia constituents and cartilage surface conditions	Murakami et al. [8]
Bearing designs for in-vivo contacts in knee joint prostheses	Kennedy et al. [9]
Investigated film interfacial formation in the contact inlet zone by synovial fluid protein aggregates	Myant & Cann [10]
Modeling and simulation of total knee replacement	Shu et al. [11]

The lubrication and wear behavior is a significant concern for the success of artificial joints, as undesirable wear debris initiates loosening and malfunctioning of joints. The artificial joint's ability to resist tissue loosening and failure due to wear debris is a crucial concern for the successful tribological performance. The lubrication and wear are portrayed overlooking each other while new cutting-edge models embracing both features could be useful. The lubricating and wear models in mixed and boundary lubrication regimes considering surface topography, deformation, wear, and asperity contact determine the superior performance of synovial artificial joints [7]. The soft-on-hard and the hard-on-hard implants are modeled considering elastic deformation as well as wear. The effective lubrication mechanisms of articular cartilage surface and synovial fluid offer extremely low friction and minimal wear in natural synovial joints. The complex structure of cartilage surface (composed of collagen and proteoglycan with high water content) and synovial fluid (composed of phospholipid, protein, and hyaluronic acid) play an important role in friction/lubrication mechanisms with contribution to high load capacity [8]. The customary knee joint prostheses materials are femoral component of cobalt–chrome–molybdenum in contact with tibial bearing of ultra-high molecular weight polyethylene (UHMWPE). The wear of tibial bearings is most acute where contact pressure is maximum and lubricant film thickness is minimum [9]. The knee joint contact interface is in the mixed lubrication regime mostly due to the thin lubricating film, and at sometimes falls into the boundary lubrication regime. The interfacial film formation of high viscosity in the contact inlet zone is driven by the synovial fluid protein aggregates in shear flow [10]. The outcomes of modeling and simulation of joint replacement during the design process of the implant are widely used to undertake in-vitro and in-vivo testing to provide insights into the implant performance [11].

The recent developments in lubrication characteristics of artificial joints are presented in Table 1.1.

1.2.1 Squeeze Film/Elastohydrodynamic Lubrication

The squeeze film/elastohydrodynamic lubrication is of significance to biological systems. There has been substantial progress made in the theoretical/numerical/

experimental studies in squeeze film/elastohydrodynamic lubrication of artificial joints. The eventual target of artificial joints lubrication is to present design guidelines for wear particles reduction. The synovial fluids in joints containing long-chain hyaluronic acid molecules are governed by micropolar fluid film lubrication theory with an increase in the effective viscosity near the cartilage porous structure [12]. The poroelastic rough cartilage considerations with couple stress synovial fluid are important in the analysis of squeeze film behavior of synovial joints [13]. The sliding surfaces conformity play an important role on the ability and mechanism of squeeze film lubrication in synovial joints [14]. The considerable elastic deformation of the sliding contacts combined with compliant tissues is accountable for lubrication at the biological surface interfaces [15]. The sliding surfaces are safeguarded by the dominant influence of micro-elastohydrodynamic lubrication in smoothing out surface asperities on the biological surfaces. The elastohydrodynamic lubrication studies should comprise a more reasonable representation of the surface roughness and synovial fluid rheology which are significant for UHMWPE/metal-on-metal artificial implants [3]. The surface topography factors may indicate likelihoods of nano-textures to improve lubrication and reduce wear, in particular for metal-on-metal implants. A number of assumptions such as no-slip/slip boundary conditions are required for analysis of artificial joints lubrication. The no-slip conditions are used for hydrophilic (metallic and ceramic) sliding surfaces, while slip conditions are used for hydrophobic (UHMWPE) sliding surfaces. It is indicated that if the lubrication regime in an artificial joint is predominantly boundary, which exists in UHMWPE-on-metal hip joints, and then the fluid film lubrication investigations are no longer pertinent. The average film thickness obtained from steady state lubrication analysis based on the average load often presents a useful estimate to the transient walking cycle [3]. The salient tribological properties of cartilage are closely linked to the musculoskeletal system properties and the lubrication regimes in cartilage spread outside the fluid film or boundary lubrication [16]. The fluid film lubrication influences the joint conformity conditions during the walking stance in knee replacements [17].

The squeeze film effects in transient elastohydrodynamic non-Newtonian lubrication of artificial knee joints helps prevent the reducing film thickness with declining surface relative velocity [18]. The minimum film thickness attained for a non-Newtonian fluid (shear thinning) is lower compared to a Newtonian fluid. The film thickness (elastohydrodynamic) increases with increasing contact area and decreasing film pressure in the artificial knee joints using ultra-high molecular weight polyethylene (UHMWPE) against metal component [18]. The minimum film thickness is larger for softer surfaces, higher viscosity, smaller load, and greater relative surface velocity during walking cycle. The analytical model permits the closed form synovial fluid film force and film thickness under the considerations of hydrodynamic squeeze motion, Darcy's permeability model, Newtonian synovial fluid [19] and non-Newtonian couple stress synovial fluid [20]. The closed form synovial fluid film force is assessed based on the synovial pressure field for the articular joints depicting the synovial fluid motion through the porous cartilage. The finite element model predictions on time dependent response of biphasic cartilage layers are influenced by the cartilage modulus and clearance, permeability, and thickness in hip joint [21]. The fluid film retention in metal-on-metal (CoCrMo balls and cups) hip prosthesis is necessary to extend lubrication ability, long term reliability and to avoid severe wear in prosthesis due to metal-to-metal contact [22]. The radial clearance is also a vital parameter as lower radial clearance enhances squeeze film retention, while a too low radial clearance induces severe contact. The articular rough cartilage influences the hydrodynamic lubrication performance of synovial knee joint throughout the gait cycle [23]. The squeeze film load of partial bearing is significantly influenced by three-layered film and couple stress fluid lubrication [24]. The novel design of squeeze-film hip implant utilizing low modulus elastic structure with high modulus metallic coatings exhibited likely alternative to conventional artificial hip implant designs [25]. The 'tribological rehydration' or fluid recovery mechanism is due to pressurization of elastohydrodynamic films and subsequently causes tissue thickening and friction reduction [26]. The articular cartilage interstitial fluid effusion is suppressed in wedge just ahead cartilage contact region that increases biphasic lubrication ability of articular cartilage [27]. The articular cartilage interstitial fluid effusion is even more suppressed near the contact region periphery at higher sliding speeds which improves cartilage lubrication due to higher interstitial fluid pressurization. The fluid pressurization generated by squeeze flow at lower speeds increases fluid load support on the biphasic lubrication of articular cartilage [28]. The effect of fluid pressurization generated by the squeeze flow pressure reduces with increasing compressive load and increases with increasing speed. The lubricated hip joint (hard metallic femoral head and polymeric acetabular cup) is analyzed in unsteady state based on mixed elastohydrodynamic lubrication with non-Newtonian fluids [29]. The wear volume in lubricated hip joint (hard metallic femoral head and polymeric acetabular cup) is evaluated by a modified Archard's model over a single gait cycle. The wear volume in lubricated hip joint (ceramic on polyethylene hip) using a lubrication-contact model (hydrodynamic-boundary) is evaluated by a modified Archard's model over a single gait cycle [30].

The recent developments in squeeze film/elastohydrodynamic lubrication are presented in Table 1.2.

1.2.2 Layered Surfaces

Synovial fluid lubrication is reliant on the formation of protein films protecting the joint surfaces. The frictional response of cartilage is regulated by the surface porosities which play a role in the interstitial pressurization of fluid inside cartilage during loading of joints [31]. The boundary friction models are formulated to theoretically explain the experimental frictional response of cartilage. The lubricant comprising only albumin (a large amount of α-helix structure) exhibited low friction in comparison to the lubricant comprising only γ-globulin (a large amount of β-sheet structure) [32]. Hence to lower both friction and wear, it is vital to apply the layered structure of γ-globulin (tight layer) at the bottom topped with albumin (layer with low shearing strength) and γ-globulin. The protein boundary layer film mainly composed of γ-globulin is enhanced by adsorption of hyaluronic acid (HA) on surface which contributes to the establishment of a stable boundary film [33]. The contribution to friction reduction is due to a gel like layer which is created due to the inclusion of hydrophilic HA molecules into boundary film. The phospholipids loss in

TABLE 1.2
Recent Developments in Squeeze Film/Elastohydrodynamic Lubrication

Squeeze Film/Elastohydrodynamic Lubrication	Authors
Synovial micropolar fluid film lubrication theory in joints	Sinha et al. [12]
Squeeze film effects of poroelastic rough cartilage with couple stress synovial fluid	Bujurke & Kudenatti [13]
Sliding surfaces conformity on the squeeze film lubrication mechanism	Mabuchi et al. [14]
Elastohydrodynamic lubrication applications in biology	Jin & Dowson [15]
Elastohydrodynamic lubrication analysis of hip implants	Jin [3]
Friction and wear of articular cartilages	Ateshian & Hung [16]
Joint conformity conditions during the walking stance	Pascau et al. [17]
Transient elastohydrodynamic non-Newtonian lubrication of artificial knee joints	Mongkolwongrojn et al. [18]
Squeeze film lubrication analytical model of the porous cartilage ankle joint with Newtonian and non-Newtonian synovial fluid	Ruggiero et al. [19], Ruggiero et al. [20]
Finite element model of biphasic cartilage layers response in natural hip joint	Li et al. [21]
Lubrication ability of the CoCrMo balls and cups specimens	Tanaka et al. [22]
Articular rough cartilage of synovial knee joint under hydrodynamic lubrication	Abdullah et al. [23]
Squeeze film load of three-layered partial bearing under couple stress fluid lubrication	Rao et al. [24]
Wear in a novel design of squeeze-film hip implant	Boedo & Coots [25]
Friction reduction attributed to fluid film rehydration	Burris & Moore [26]
Friction coefficient and load capacity of poroelastic model with biphasic synovial fluid lubrication	Horibata et al. [27], Horibata et al. [28]
Wear in lubricated hip replacements with contact models	Ruggiero et al. [29], Ruggiero & Sicilia [30]

osteoarthritis joints has consequence to hydrophobicity deficiency. The lower coefficient of friction is attained on a surface comprising phospholipid bilayer with higher wettability [34]. The lubrication mechanism of the joint is influenced by the lubricant's pH and interfacial energy with a consequent influence on coefficient of friction. The synovial joint cartilage integrity is due to secretion of phospholipid multibilayer surface coating on the cartilage surface as solid lubricant delivering hydration boundary lubrication [35]. The ultra-high molecular weight polythene (UHMWPE) plate surface grafted with a polymer membrane extends the useful lifespan of artificial joints. The large water-retaining ability of the porous hydrophilic 2-methacryloyloxyethyl phosphorylcholine (MPC) graft-polymerized membrane with finely porous inner structure provides lubrication and serves to reduce wear in the UHMWPE component [36]. The main factors to enhance hydrodynamic lubrication performance and to reduce the dry contact in metal-on-metal hip bearing implant surfaces are diametral clearance and diameter. An aspherical 'alpharabola' metal-on-metal hip-bearing implant surface generates a thicker lubricant film thickness when compared to a spherical conventional hip bearing implant surface [37]. A significant decrease in the dry contact is attained in an aspherical metal-on-metal hip-bearing implant surface with appropriate selection of geometric parameters.

The proteins increase the film thickness with time (rolling distance) for a metal ball compared to a ceramic ball under pure rolling conditions [38]. The proteins increase the film thickness swiftly with time (rolling/sliding distance) and the film thickness starts to dip by a few nanometers after the maximum film thickness is attained under rolling/sliding conditions. The mechanism of surface film development under static conditions is through adsorption, while the film development under dynamic conditions occurs through protein aggregation. The film thickness increases with increasing adsorption mass and adsorption rate under rolling conditions [39]. The adsorption mass, adsorption rate, and film thickness are reduced due to increasing pH. In the comparison of lubricants macromolecular solutions (HA, mucin, or lubricin), the mucin shows improved performance compared to the HA or lubricin [40]. The signs of wear or changes in topography are not noticed by utilizing mucin for lubrication of the cartilage surfaces. The synergistic combination of various lubrication modes (boundary, gel, biphasic, and hydration) from the boundary to film lubrication appears to promote the superior tribological characteristics in natural synovial joints [41]. The synovial constituent albumin plays a leading role in pure rolling thus enhancing the film thickness [42]. The albumin and γ-globulin enhance the film thickness at lower speeds, while the effect of γ-globulin is not significant at higher speeds. The synovial constituents albumin, γ-globulin, phospholipids, and HA, play a leading role in noticeably influencing the lubricant boundary film [43]. The γ-globulin jointly with HA form a comparatively thin stable boundary film allowing the improved adsorption of albumin, and thus enhancing the lubricant boundary film. The albumin and γ-globulin proteins in interface between the femoral knee implant metal and real polymer insert are examined to be of importance [44]. A better tribological performance is achieved by supplementing organic constituents to the surface-lubricant contacts which have influencing roles on the frictional and material volume loss [45]. The principal mechanism of lubrication influencing the protection of surfaces during rubbing is the formation of denatured insoluble protein films [46]. The denatured insoluble protein lubricating films are induced into the contact region due to inlet shear. The long-life design of artificial joints essentially requires accomplishment of effective biolubrication. The structural integrity of small unilamellar vesicles adsorbed on the silicon nitride (Si3N4) surfaces is linked effectively with exceptional lubrication abilities of liposomes with longer carbon chain length [47]. The exceptional lubrication abilities of liposomes are also due to the boundary layer formed due to the synergistic interface of liposomes and biocompatible negative-charged polymer. The friction and wear of ultra-high molecular weight polyethylene (UHMWPE) surface adsorbed with proteins is increased due to the change in the predominant abrasive to adhesive wear mechanism [48]. However, the wear of ultra-high molecular weight polyethylene (UHMWPE) surface is increased when mixing proteins with phospholipids and HA, due to the enhanced the entrainment of the proteins in the contact area. The friction is increased with phospholipids while the friction is reduced with HA with increasing lubricants' viscosity. Phospholipids bilayers in cartilage boundary can reduce friction by means of hydration lubrication [49].

TABLE 1.3
Recent Developments in Biotribology of Layered Surfaces

Layered Surfaces	Authors
Friction model for articular cartilage boundary	Ateshian et al. [31]
Albumin or γ-globulin in natural synovial fluid	Nakashima et al. [32]
Lubricant composition on proteins adsorption and stability	Yarimitsu et al. [33]
Mechanisms of lubrication of phospholipids-bilayer of cartilage	Pawlak et al. [34], Pawlak et al. [35]
Grafted polymer membrane onto UHMWPE plate	Sawano et al. [36]
Aspherical metal-on-metal hip bearing implant surface	Meng et al. [37]
Proteins effect on film formation	Vrbka et al. [38]
Mechanisms of film formation of proteins in synovial fluids	Parkes et al. [39]
Lubricants macromolecular solutions comparison	Boettcher et al. [40]
Boundary, biphasic, gel, and hydration lubrication modes	Murakami et al. [41]
Mechanisms of lubrication of protein film in ceramic femoral heads	Nečas et al. [42]
Mechanisms of lubrication in hard-on-soft hip artificial joints	Nečas et al. [43]
In situ lubricant development in knee joint replacements	Nečas et al. [44]
Protein-metal interactions on tribofilm formation	Taufiqurrakhman et al. [45]
Artificial joint lubrication with bovine calf serum and human synovial fluid	Stevenson et al. [46]
Lubrication mechanisms between biomimetic surfaces	Wang et al. [47]
In-vivo tribology of implant joint prostheses	Shinmori et al. [48]
Phospholipids in lubrication of cartilage boundary	Cao et al. [49]

The recent developments in biotribology of layered surfaces are presented in Table 1.3.

1.2.3 Hydrogels

Hydrogels with suitable properties are potential materials for cartilage repair. Synthetic hydrogels have potential applications for articular cartilage as well as a developing cartilage in a damaged joint. The wear of synthesized poly(2-hydroxyethyl) methacrylate (polyHEMA) hydrogels increases with increasing applied load and hydration, while the wear of hydrogels decreases with increasing cross-link density [50]. The friction and wear of poly (vinyl alcohol) hydrogel for artificial cartilage depends on protein contents in lubricants. The friction properties of bovine serum albumin comprising the α-helix structure is lower compared to human gamma globulin comprising the β-sheet structure in mixed/boundary lubrication regime [32]. The β-sheet structure is strongly adsorbed on poly (vinyl alcohol) hydrogel, while the α-helix structure lacks adsorption ability (as the α-helix structure is easily released from surfaces due to low cohesive strength of formed shear layer). Lower friction artificial cartilage is maintained with a layered structure of a blend of various proteins. Soft biomaterials are frequently employed in applications that include contact of biological tissues. In the investigations of friction coefficients of soft hydrogel biomaterials, the lower friction coefficients were noted on undamaged cells and higher friction coefficients were noted on damaged cells [51]. The salient parameters to establish the wear performance of hydrogels are cross-link density and hydration. The wear phenomena in most compliant hydrogels is adhesive wear, while the wear phenomena with increasing cross-linking density and reducing water absorption capacity of hydrogels, is abrasive wear [52].

The low friction and wear in artificial cartilage interface contacts is maintained by adsorbed film formation (at micro/nano levels) in mixed/boundary lubrication regime [53]. The presence of albumin and γ-globulin constituents exhibited the lowest friction in the mixed regime of lubrication. The low friction and wear in the articular cartilage are maintained by proteoglycan gel film as a consequence of hydration lubrication mechanism even after removal of adsorbed layer [54]. The hydration lubrication with protein adsorbed film is effectual when restarted under loading. The friction and wear characteristics of articular cartilage in mixed/boundary lubrication regime are significantly influenced by adsorbed layer formed on a gel film at articular cartilage in synovial joints. In the absence of adsorbed layer, the proteoglycan gel film is likely to maintain low friction and wear of bulk articular cartilage with an efficient hydration mechanism of lubrication. The friction in articular cartilage is lowered by the mechanism of biphasic lubrication [55]. The larger friction coefficients for the hydrogels considering elastic effects are recognized as the outcome of the greater interface of the intra/inter-polymer chains generated by the higher degree of polymerization and saponification value [56]. The larger friction coefficients for the hydrogels under hydrodynamic lubrication are recognized as the outcome of the lower hydrophilicity of the poly(vinyl alcohol) hydrogels with lower saponification value at relatively lower load and higher velocity. The exceptionally low friction and wear in natural synovial joints are maintained by their outstanding lubricating capability which appears to be a synergistic blend of multimode mechanisms such as boundary, gel film, hydration, biphasic, and/or fluid film lubrication [57]. However, in artificial joints comprised of ultra-high molecular weight polyethylene against metal/ceramic material, contact of interfaces in boundary and/or mixed lubrication mechanism generates high friction and wear. The improvement in friction and wear characteristics through artificial biomimetic hydrogel cartilage, such as poly(vinyl alcohol) hydrogel, is required to prolong the durability and life of an artificial joint [57]. The wear resistance of ultra-high molecular weight polyethylene for total joint prostheses has been enhanced with recent developments of material technologies. The artificial hydrogel cartilage with identical properties to natural articular cartilage is expected to solve the friction and wear problems by enhancement of lubrication mechanism with excellent tribological behaviors. The tribological behaviors of artificial cartilage material, ellipsoidal poly(vinyl alcohol) hydrogel, evaluated against glass plate in saline solution are as follows [58]: hybrid (CD on FT) method < cast-drying (CD) method < freeze-thawing (FT) method < hybrid (FT on CD) method. PVA hydrogels prepared by the hybrid (CD on FT) method displayed exceptionally low friction and wear. The tribological behaviors of ideal artificial cartilage material, poly (vinyl alcohol) (PVA) hydrogel, evaluated in ultra-pure water are as follows [59]. PVA hydrogels prepared by (i) FT method exhibited high friction coefficient and wear, (ii) CD method exhibited low friction coefficient with scratches, and (iii) hybrid method (i and ii) exhibited the lowest friction coefficient and minimum wear.

Polyvinyl alcohol (PVA) hydrogels display outstanding tribological characteristics and are opted as potential biomaterials to replace damaged articular cartilage due to their low coefficient of friction and wear, high permeability, and superior biocompatibility [60]. The surface characteristic of alloys plays a significant role in friction coefficient reduction, and the alloys are grouped according to the surface oxide compositions as Ti-oxide-surface alloys and Fe/Cr-oxide-surface alloys [61]. Based on the wettability test, Ti-oxide-surface alloys show higher polar components of surface free energy than Fe/Cr-oxide-surface alloys. The elastic friction coefficients are governed by the hydrogel polymer adsorption, and Ti-oxide-surface alloys show lower friction coefficients than those of Fe/Cr-oxide-surface alloys [61]. The mechanical rigidity and strength of the structural hydrogel materials are taken into account for diverse biotribological applications. The structural hydrogel materials originate with low polymer mesh size and high polymer concentrations, that causes high friction coefficients under aqueous environments [62]. The large mesh size, flexible and soft polyhydroxyethylmethacrylate (pHEMA) hydrogels will be able to deliver ultra-low friction, but at the loss of mechanical strength. The entangled networks of polymer will be able to deliver reduced coefficient of friction. The swift reinstatement of biotribological and biomechanical functions endures a noteworthy test for articular cartilage restoration. The poly (vinyl alcohol) (PVA) hydrogel is considered as a prospective articular cartilage substitute for its low friction and fair strength [63]. The coefficient of friction decreased with adding up of ploy (lactic-co-glycolic acid) (PLGA) content. The low friction coefficient of the composite hydrogel on the UHMWPE surface under biphasic lubrication is due to its porous configuration with sizable water content [64]. The friction and drag at the interface are effectively reduced due to the shear of the hydrogel surface which is caused by the structural changes related to the surface chains alignment [65]. The phospholipid is a hydrophilic membrane with a negatively charged surface (-PO4−) formed by adsorption of articular cartilage surface-active phospholipid (SAPL) molecules to negatively charged proteoglycan matrix [66]. The friction in Gemini hydrogel configurations made from polyacrylamide (PAAm) formulations under direct sliding contact increases with increasing viscosity and decreasing mesh size with decreasing temperature [67]. The fiber-reinforced structure is potential biomimetic articular synovial cartilage materials that take part a vital role in enhancing the fluid load support and frictional properties. The fiber-reinforced poly(vinyl alcohol) (PVA) hydrogel reinforced with surface PVA fiber layers have a low friction coefficient [68]. The friction characteristics of hydrogel brushy surfaces are reliant on the interface contacts and surface hydration intensity. The friction characteristics of acrylamide hydrogels in sliding at low pressure contacts is due to the mechanism of interfacial shearing of the liquid film, rather than viscoelastic or poroelastic dissipation [69]. The mechanism of deformation induced poro-elastic flow is substantial at high pressure contacts. The double-network physically cross-linked poly (vinyl alcohol)-(nano-hydroxyapatite)/(2-hydroxypropyltrimethyl ammonium chloride chitosan) hydrogel with presence of nano-hydroxyapatite (HA) displayed lower coefficient of friction and wear properties, and exceptional cytocompatibility [70].

The recent developments in biotribology on hydrogels are presented in Table 1.4.

TABLE 1.4
Recent Developments in Biotribology on Hydrogels

Hydrogels	Authors
Poly(2-hydroxyethyl) methacrylate hydrogels	Freeman et al. [50]
Investigations of proteins on friction	Nakashima et al. [32]
Soft hydrogel biomaterial surfaces investigations	Dunn et al. [51]
Tribological properties of synthetic hydrogels	Bavaresco et al. [52]
In situ examination of adsorption behavior of proteins	Murakami et al. [53]
Adsorbed layer and gel film on articular cartilage	Murakami et al. [54]
Biphasic and hydration lubrication mechanism	Murakami et al. [55]
Poly(vinyl alcohol) hydrogel	Mamada et al. [56], Murakami et al. [57], Murakami et al. [58], Yarimitsu et al. [59], Sardinha et al. [60]
Tribology of medical devices in contact with soft tissue	Kosukegawa et al. [61]
Polyhydroxyethylmethacrylate (pHEMA) hydrogel	Pitenis et al. [62]
Semi-degradable porous hydrogel	Cao et al. [63]
Composite hydrogel on the UHMWPE surface	Chen et al. [64]
Structural change effects/local dehydration	Kim & Dunn [65]
Articular cartilage hydrophilic surfaces	Mreła & Pawlak [66]
Polyacrylamide Gemini configurations	McGhee et al. [67]
Poly(vinyl alcohol) (PVA) hydrogel with PVA fibers	Sakai et al. [68]
Polyacrylamide hydrogel lubrication	Simič et al. [69]
Dual physically cross-linked hydrogels with double-network	Gan et al. [70]

1.3 BIOTRIBOLOGICAL CHARACTERISTICS OF TEXTURED SURFACES

Owing to the advances in surface preparation/modification/coating techniques, surface texture designs have been employed to take advantage of tribological performance. The surface texturing has prospects of improving the tribological behavior of metal-on-metal hip joint replacements or smooth ultra-high molecular weight polyethylene (UHMWPE) total joint replacements. Micro-textures and diamond-like carbon coatings are prominent surface preparation/modification/coating techniques for biotribological orthopedic implants in order to lower friction and wear.

Biomimetic approaches embracing tribology (friction, wear, and lubrication), mimic the lessons learned from the fascinating biological and tribological features of natural systems [71]. The prospects of application of biomimetic approaches in tribology have been impressive, with closer association between biomimetics and biotribology. The bionic surfaces are in great demand to realize or exceed specific functionalities of creatures in nature with superb tribological designs [72] such as: the anisotropic friction design (e.g. claws of animals), adhesion due to van der Waals forces (e.g. gecko), super hydrophobic surfaces (e.g. lotus leaf), composite structures (e.g. pangolin), lubricious mucus (e.g. fish) and wedge-shaped scales (e.g. sharks). Understanding tribology of biological systems is very crucial to generate bionic surfaces with similar or exceeding tribological behavior. The computer modeling and

TABLE 1.5
Recent Developments in Biotribology of Textured Surfaces in Implants

Textured Surfaces in Implants	Authors
Biotribological fascinating features	Dowson & Neville [71]
Creatures with tribological designs	Liu et al. [72]
	Tang & Zhang [73]
Bio-inspired nanofunctionalized surfaces	Xie [74]
Biocompatibility in the design of soft medical implants	Pitenis & Sawyer [75]
Orthopedic textured biomaterial surfaces	Allen & Raeymaekers [76]

simulations of interface and surface interactions will lay foundation for developments of bio-surface/bio-interface applications [73].

The potential way out to resolve the clinical complications related to biomaterials is provided by nanofunctionalization approaches to fabricate. The biomaterials with bio-inspired nanofunctionalized surfaces imitate not only the physical constructions, but also the chemical compositions in nature, which can be used successfully in the areas of cartilage repair and bone regeneration [74]. The implant biocompatibility should be taken into consideration in the design of roughness and texturing of soft medical implants [75]. The innovative methods to reduce wear to the bearing surfaces are to add a microtexture patterns, coatings, and highly cross-linked polyethylene materials [76]. The microtexture pattern features on orthopedic implant biomaterial surfaces are viable with advances in manufacturing.

The recent developments in biotribology of textured surfaces in implants are presented in Table 1.5.

1.3.1 Micro-Dimple Surfaces

The micro-dimple surfaces have a potential beneficial influence on the reduction of asperity contacts in implants, predominantly under boundary lubrication regimes. The dimples on the metal femoral head fabricated using electrical discharge etching lower the polyethylene wear in hip implants [77]. The primary source of UHMWPE wear/scratch marks is the Co–Cr–Mo alloy particles in sliding interface. A micro-dimpled UHMWPE sliding surfaces inhibits the wear/scratch marks by entrapping the wear particles in dimples [78]. The dimple configurations assist in lowering of polyethylene wear in hip implants by decreasing abrasive wear and enhancing lubricant supply. The dimple surfaces in metal-on-metal hip implants under the mixed elastohydrodynamic lubrication conditions significantly influence the asperity contacts and film thickness [79]. In comparison to plain/dimpled artificial implants, the micro-dimple implant surfaces coated with diamond-like carbon (DLC) under an osteoarthritis-oriented synovial fluid (OASF) lubrication generated lower coefficient of friction and wear [80]. The micro-dimple implant surfaces coated with DLC displayed a lower rate of increasing friction coefficient with increasing load due to the development of graphite transfer film (graphitization) on the coated surfaces. The tribological performance of micro-dimple implant surfaces are significantly

TABLE 1.6
Recent Developments in Biotribology on Micro-Dimpled Surfaces

Micro-Dimpled Surfaces	Authors
Dimples on metal femoral head	Ito et al. [77]
Micro-dimples to reduce UHMWPE wear	Sawano et al. [78]
Dimples in metal-on-metal hip prosthesis	Gao et al. [79]
DLC coated micro-dimples	Ghosh et al. [80]
Micro-dimples in ceramic-on-ceramic hip prosthesis	Roy et al. [81]
DLC coated micro-dimples against ceramic cups	Choudhury et al. [82]
Cr-coated glass disk against micro-dimples on steel ball	Choudhury et al. [83]
Micro-dimples on femoral heads	Choudhury et al. [84]
Micro-dimples on CrCoMo femoral heads in hip joint	Choudhury et al. [85]

influenced by surface wettability and lubricant viscosity. The ceramic-on-ceramic hip prosthesis with micro-dimples of large diameter and high density under bovine serum lubrication exhibited substantial decrease in coefficient of friction and wear [81]. The micro-dimpled DLC coated prosthesis heads against ceramic cups enhanced the tribological behavior of artificial hip joints [82]. The micro-dimpled DLC coating yielded an insignificant change in surface roughness and decreased abrasive third body wear rate against ceramic cups. A substantial reduction in coefficient of friction of the micro-dimpled DLC coated heads against ceramic cups is revealed compared to a micro-dimpled metal (CoCr) heads against ceramic cups. The micro-dimples maintain lubrication resulting in minimization of wear [83]. The DLC promotes scuffing-free surfaces with lower friction coefficient but with minor lubricant film formation (boundary lubrication under the nonconformal contact). The combination of micro-dimples and DLC should be taken into account to maximize tribological performance (reduced friction and wear). The metallic micro-dimpled femoral heads against a metallic cup yielded significantly lower coefficient of friction, while the metallic micro-dimpled femoral heads increased the coefficient of friction against a polyethylene cup [84]. The mechanism of improved film formation in micro-dimpled arrays influenced the friction reduction. The lubricant film thickness in artificial hip joints with micro-dimples on CrCoMo femoral heads is appreciably higher than the contact interface roughness indicating hydrodynamic lubrication [85].

The recent developments in biotribology on micro-dimple surfaces are presented in Table 1.6.

1.3.2 Micro Pattern Surfaces

The prosthetic joints surfaces with texture pattern designs mimic the natural articular cartilage which exhibits microtexture surfaces with shallow indentations. The honed surface textures demonstrate lower coefficients of friction in comparison to non-textured surfaces due to enhanced lubricant film thickness and reduced third body abrasive wear [86]. The width, depth, and number of grooves of honed surface textures affect the coefficient of friction and wear rate in metal-on-metal hip joints using a lubricant with viscosity similar to that of pseudo-synovial fluid. The honed surface textures demonstrate lower coefficients of friction during transient walking cycles proving their potential application in metal-on-metal hip joints for improved hip implant longevity [87]. The surface wettability behaviors of laser textured specimens are attained in the range of superhydrophobic to superhydrophilic. The surface wettability behaviors of laser textured Co–Cr–Mo specimens have excellent wear resistance in bovine serum albumin (BSA) solution [88]. The wear of textured surfaces with wettability is lesser than that of the untextured surfaces. The microtexture patterns on the femoral component of a prosthetic knee joint enhances the bearing load and film thickness, thus ensuing decreased friction between the knee bearing surfaces [89]. The microtexture designs on a femoral component also revealed that the friction in a prosthetic knee joint is decreased taking into account of the polyethylene tibial insert deformation.

The texturing design, based on the two-dimensional solution of transient Reynolds equation, can be successfully employed to enhance lubrication effects of UHMWPE surfaces [90]. The coefficient of friction is appreciably influenced by the surface texture (of the harder counterpart) and the transfer film development in sliding of ultra-high molecular weight polyethylene (UHMWPE) pins against steel plates [91]. The textured surfaces deliver lowered coefficient of friction of carbon-fiber-reinforced polyether ether ketone (CFR-PEEK) compared to the plain surfaces, which is apt for the advancement of acetabular cup designs [92]. Surface texture reduces friction and increases load of mechanical seals, as well as brings about the denatured protein accumulations on the sealing surface. The lower (and stable) frictional properties assuring a higher critical load are achieved in the mechanical seals in ventricular devices by surface texture pattern designs followed by DLC coating [93]. The benefits from surface texture pattern designs on sliding wear of lateral contact area of the polyethylene soft surface (tibial insert) in metal-on-UHMWP knee joint is evaluated using mixed elastohydrodynamic lubrication model [94]. The micro-texture patterns are designed based on elastohydrodynamic lubrication model to increase hydrodynamic pressure and lubricant film thickness in a hard-on-soft bearing [95].

The recent developments in biotribology on micro-pattern surfaces are presented in Table 1.7.

TABLE 1.7
Recent Developments in Biotribology on Micro-Pattern Surfaces

Micro Pattern Surfaces	Authors
Honed surface textures in metal-on-metal hip joints	Choudhury et al. [86], Choudhury et al. [87]
Wettability of textured Co–Cr–Mo surfaces	Qin et al. [88]
Micro-textures in deformed polyethylene tibial insert	Qiu et al. [89]
Texture designs on UHMWPE surfaces	Zhang et al. [90]
Texture and roughness effects on UHMWPE surfaces	Menezes & Kailas [91]
Surface textures on CFR-PEEK for acetabular cups	Wyatt et al. [92]
Surface texture designs of seals with DLC coating	Kanda et al. [93]
Texture designs of metal-on-UHMWP knee joint	Gao et al. [94]
Microtexture patterns in a hard-on-soft bearing	Allen & Raeymaekers [95]

1.3.3 Bionic Surfaces

The amazing properties of biological systems in nature are a significant foundation of motivation to advance artificial techniques of textured surfaces that can accommodate lubricant as well as trim down the frictional area of contact. The design of biomimetic textured surface with shark skin, body, and rib morphology provides good frictional performance and lubrication characteristics [96]. The lubrication theory models are established to evaluate the influence of geometric parameters of biomimetic surfaces on tribological behavior. The prospects of bionic design stem from the multi-scale dental anti-wear mechanism produced by the exclusive hierarchical structure, self-repair process, salivary pellicle lubrication and hydration proteins [97]. Bionic texturing improves the nanohardness of the modified surface layer biotribological properties. Bionic texturing on Ti6Al4V alloy reduces the friction coefficient and increases wear resistance of the surface modified layers [98].

The geometrical characteristics of hexagonal textures modeled using “X” shaped cells have a significance impact on the tribological performance. The hexagonal texture density has noteworthy influence in the friction coefficient reduction under full film lubrication regime [99]. The concept of blending diverse bionic features within a sample is based on rigorous examinations of some species that have disclosed microstructure properties of adhesion on surfaces [100]. The blending diverse biomimetic microstructure features, such as micro-shaped (mushroom and wall), are based on the optimized properties of adhesion on surfaces. The optimized surfaces with diverse bionic features achieved enhanced friction and adhesion performance in comparison to those comprised with the non-optimized/same surface features [100]. The high reciprocating velocity piston pair with superior frictional performance is attained with the various parametric arrangements of mimicking fish scale texture [101]. A representative mathematical model of mimicking fish scale texture is formed on the understanding of characteristic function approximation and coordinate transformation. The fish scale texture effects with superior frictional performance on the high reciprocating velocity piston pair are obtained using experimental design and simulations. The microrectangular pocket pad bearing together with fish scale texture design yields significant increase in minimum film thickness and decline in friction coefficient as assessed against the other pad designs [102].

The recent developments in biotribology on bionic surfaces are presented in Table 1.8.

TABLE 1.8
Recent Developments in Biotribology on Bionic Surfaces

Bionic Surfaces	Authors
Biomimetic surface of shark skin, body, and rib morphology	Lu et al. [96]
Bionic design prospects of dental anti-wear performance	Zhou et al. [97]
Bionic texturing for modified surface layers	Wang [98]
Hexagonal textured surfaces	Zhong et al. [99]
Biomimetic adhesive microstructure combinations	Badler & Kasem [100]
Piston model with fish scale texture	Quan et al. [101]
Fish scale texture microrectangular pocket pad design	Atwal and Pandey [102]

1.4 TRIBOLOGICAL CHARACTERISTICS OF IMPLANTS

There is significant attention in decreasing the severe wear through the use of enhanced materials and alternate designs of total replacements joints [103]. The polyethylene wear debris has been related to the tribological process in implants of the metal-on-polymer arrangement. The advancements of in-vitro models are vital to be familiar with the tribological characteristics, substitution, and treatments of cartilage [104]. The graphene-materials (graphene-oxide and reduced graphene-oxide) and graphene-nanocomposites have invited great attention with promising tribological, mechanical and biocompatibility properties [105]. In addition to the implant design and material selection, there are numerous important biotribological parameters that can significantly influence the wear of articulating surfaces with large joint replacements and total disk replacements [106]. The mechanism of tribological phenomena of biomaterials comprising alloys, ceramics and polymers necessarily emphasized in order to fabricate artificial biomaterials to replace the damaged tissues in human body [107]. The biotribological tests of thermally oxidized titanium alloy revealed potential applications in artificial joints with improved friction and wear performance characteristics [108].

The changes in translational (anterior–posterior) and rotational motion (internal–external) limits the tibio-femoral knee joint kinematics and wear behavior of a mobile bearing posterior stabilized knee design [109]. The hip joint models for the dry and lubricated revolute joints are employed for the interaction of kinematic and dynamic response of femur head inside the hip bone or acetabulum [110]. The intrajoint force peaks observed with the dry hip model are related to the multiple impacts of the femur head and the cup. The hip joint system's response has a tendency to be smoother in the presence of the lubricant, due to the synovial fluid damping mechanism.

Surface roughness of knee prostheses has been proposed as the mechanism for premature tribological prosthesis failure in total knee joint replacement performance. The roughness of tibial ultra-high molecular weight polyethylene of retrieved knee implants is characterized to assess the tribological failure in knee joint replacements [111]. The roughness dissimilarities are quantified between medial and lateral condyles taking into consideration the load experience differences of the two condyles. The biotribological performance of the hip implants recovered from patients after implantation is assessed by metal transfer characterization on the ceramic femoral head bearing surfaces [112]. The reactivity at the surface structure of the metal interface in artificial hip joints is improved by surface interaction due to friction. The formation of the tribofilms developed by surface interactions can be categorized by various arrangements of organic layers and oxide films [113]. The formation of surface reaction tribolayer establishes a way to minimize wear of CoCrMo for metal-on-metal hip implants.

The recent developments in biotribology of orthopedic implants are presented in Table 1.9.

TABLE 1.9
Recent Developments in Biotribology of Orthopedic Implants

Orthopedic Implants	Authors
Metal-on-polymer wear in joints	Dowson [103]
Articular cartilage biotribology	Katta et al. [104]
Graphene-materials and graphene-nanocomposites	Dong & Qi [105]
Biological articulating surfaces wear	Harper et al. [106]
Biomaterials of alloys, ceramics, and polymers	E et al. [107]
Wear resistance of titanium alloy by thermal oxidation	Luo et al. [108]
Mobile bearing posterior stabilized knee design	Grupp et al. [109]
Femur head interaction inside the hip bone	Costa et al. [110]
Roughness characterization of retrieved knee implants	Ruggiero et al. [111]
Metal transfer characterization on ceramic femoral heads	Affatato [112]
Metal-on-metal hip joint in-vitro and in-vivo studies	Espallargas et al. [113]

1.4.1 Coatings

The tribological behaviors of the bioceramics are enhanced against ultra-high molecular weight polyethylene (UHMWPE) in human plasma lubrication [114]. The lower wear rate of UHMWPE in human plasma lubrication is due to the protein deposited on the surfaces. The bioceramic compositions of sintered HA/yttria-partially-stabilized zirconia composite against UHMWPE in human plasma lubrication yield an optimum minimum friction coefficient and wear rate and maximum hardness. Bioceramic coatings are utilized to enhance the wear, mechanical and biological characteristics of bone implants [115]. The benefits of HAp-TiO2 compact coatings, with less amorphous phase contributes to lower wear rates and higher friction coefficients for better implant fixation, and thus ensures the integrity of the bioceramic coating. A wear-resistant formulation of silicon nitride and silicon carbon nitride coatings for hard-bearing implants surfaces can potentially extend the implant lifetime [116]. The wear resistance of silicon nitride coatings is similar to that of bulk silicon nitride (hardness of silicon nitride coatings is similar to that of sintered silicon nitride) and significantly higher than that of cobalt chromium (elastic modulus of silicon nitride coatings is similar to that of cobalt chromium). The multilayer surface zirconium nitride coating with carbon-fiber-reinforced poly-ether-ether-ketone (CFR-PEEK) is used to enhance the wear performance of knee joint system [117]. The biotribological performance of CFR-PEEK/ZrN multilayer surface coating in a knee joint system yielded low wear and negligible surface fatigue. The DLC is a potential material to improve wear resistance characteristics in orthopedic implant treatments. The hydrogenated amorphous carbon (a-C:H) has moderate elastic modulus and high hardness with relatively high hardness/elasticity ratio which enables the film to conform well with the substrate [118]. The a-C:H coated pin against counterface (a-C:H coated) showed low coefficient of friction due to the transfer film formation which is attributed to degree of graphitization with increasing applied load. The a-C:H coated surface also displays hydrophilic features for protein absorption. Significantly low friction coefficient and good wear resistance (good adhesion between the substrate and coating) of the coated layer against the alumina counterface is observed [118]. The DLC-layered coatings with improved surface/material properties (ratio of hardness vs elasticity) and absorbed protein portrayed a very important role in the tribological characteristics appropriate for orthopedics implants [119]. The layered coatings acquired columnar and very fine-grained microstructures with micro-cracks of very low inter-columnar density. The DLC (a-C:H) layers are noticed to produce outstanding tribological characteristics at "DLC on Polyethylene/DLC" sliding pairs under hip joint simulated circumstances. The DLC coatings with interlayers (Zr and ZrN (Zr:ZrN) sublayers, Zr and DLC (Zr:DLC) and N-doped DLC layer) on titanium alloy (Ti-6Al-4V) are employed for advancing the biotribological functioning of orthopedic implants [120]. The Zr:ZrN layer is intended for augmenting load capacity and corrosion resistance; the Zr:DLC layer is aimed for gradual stress transition and enhancing layer adhesion thus reducing DLC delamination from the substrates; and the N-doped DLC layer is for reducing friction and wear. The hydroxyapatite (Fe-HA) in tooth enamel is comprised of iron and thus displays good hardness and high wear resistance [121]. The Fe-HA ceramics exhibited better wear resistance when compared with the pure HA ceramics. The iron content has a considerable effect on the crystal structure and morphology of Fe-HA powders. Titanium alloys are extensively used in the clinical purpose of artificial joints, and their wear resistance is improved with the deposition of DLC film on titanium alloy surface. The wear mechanisms of DLC films on Ti6Al4V alloy surface involved fatigue, abrasive, and adhesive wear [122]. The chitosan coating surface under several sliding speeds displayed lower friction coefficient in comparison with the uncoated surface [123]. The culturing of coated super hydrophilic surface with osteoblast cells favored adhesion and good proliferation of cells. The multi-walled carbon nanotubes (MWCNTs) generated microstructural amendments in plasma electrolytic oxidation coating yielded low friction and reduced wear damage [124]. The MWCNTs' enhanced coating tailors surface properties such as dense barrier layer and irregular porosities and reinforcement that reduce the coefficient of friction and wear in comparison to a MWCNT-free coating.

The recent developments in biotribology on implant coatings are presented in Table 1.10.

1.4.2 Surfaces

Metal-on-metal (MOM) hip joint bearings have established low wear rates, nevertheless, wear of MOM joints is apprehensive due to the biological reaction and toxicity of wear debris. The DLC and PVD coatings guards the femoral heads lowering wear in comparison to the MOM femoral heads [125]. The stem–cement interface debonding arises certainly for all stem designs under physiological loading. The wear debris produced at the stem–cement interface reveals an increasing importance in the mechanical failure of cemented total hip replacements [126]. The friction coefficient is dependent on the surface finish, with a low value obtained for the polished contacting surfaces. The proteins from the calf serum are found to

TABLE 1.10
Recent Developments in Biotribology on Implant Coatings

Implant Coatings	Authors
Hydroxyapatite (HA) nanoparticles synthesis	Wang et al. [114]
Compact coatings integrity with less amorphous phase	Melero et al. [115]
Silicon nitride and silicon carbon nitride coatings for hard bearing implants surfaces	Pettersson et al. [116]
Zirconium nitride multilayer surface coating with carbon-fiber-reinforced poly-ether-ether-ketone	Grupp et al. [117]
Hydrogenated amorphous carbon (a-C:H) on alumina	Hee et al. [118]
Diamond-like carbon coatings (DLC) on orthopedic implants	Choudhury et al. [119]
DLC coatings with interlayers of zirconium on titanium alloy	Choudhury et al. [120]
Influence of iron on wear resistance of nano-hydroxyapatite	Han et al. [121]
Deposition of DLC film on Ti6Al4V alloy surface	Xu et al. [122]
Layer-by-layer deposition on CoCrMo alloy with grafting	Qin et al. [123]
Coating structure with tailoring surface properties using multi-walled carbon nanotubes (MWCNTs)	Daavari et al. [124]

adsorb onto both the bone cement surfaces and femoral stem. The wear at the stem–cement interface may be improved by tailoring physicochemical properties of the femoral components to promote protein adsorption. The effect of bovine calf serum (BCS) and human synovial fluid (HSF) fluid compositions are assessed for friction and wear of cobalt chromium molybdenum (CoCrMo) materials. The cobalt chromium molybdenum (CoCrMo) material pairs recorded higher wear for the HSF samples compared to BCS fluid compositions [127]. The wear scar size on the CoCrMo material is dependent on protein content which reduced appreciably for higher BCS concentration. The protein deposits are adherent which established the significance of proteins in determination of CoCrMo wear [127]. The anterior–posterior translation and internal–external rotation influences the wear of knee implants. The two wear models, contact pressure independent and dependent models, are employed in conjunction with finite element numerical model for wear prediction. The contact pressure independent model shows decreased wear during forward movement of the tibial insert in flexion, while the contact pressure dependent model shows increased wear [128]. The results predicted by the contact pressure dependent model are consistent with those of reported experimental wear trends. The precise quantification of bearing material deficiency from MOM retrieved hip replacement implants is fundamental to identifying their failure. The geometrical methods are the viable approaches to assess volumetric wear (material loss) from the retrieved bearing hip implants [129]. The key concern influencing joint prosthesis is wear, bringing about loosening and implant failure. The joint load distributions have presented important understanding that the knee loading configurations, exhibiting different contact joint loads in medial and lateral condyles [130]. The surface roughness is not appreciably dissimilar relating medial and lateral sides, nevertheless, surface damage is higher in the lateral condyles than in the medial condyles. The implant surface roughness affects the early wear and metal transfer surface area. Based on the roughness factors taken into account on the articular surface, the metal transfer regions were rougher than the

TABLE 1.11
Recent Developments in Biotribology on Implant Surfaces

Implant surfaces	Authors
Hip prostheses with thin hard coated metallic heads	Ortega-Saenz et al. [125]
Biotribological stem–cement interface properties	Zhang et al. [126]
Hip implants under reciprocating sliding conditions	Stevenson et al. [127]
Anterior–posterior translation and internal–external rotation influence on the knee implants wear	Zhang et al. [128]
Volumetric wear estimation from hip implant bearing	Bergiers [129]
Implant surface roughness influences the metal transfer surface area and premature wear	Affatato et al. [130], Affatato [112]
Total knee arthroplasty medial and lateral wear	Affatato et al. [131]
Ceramic-on-ceramic hip implant	de Villiers & Collins [132]

non-metal transfer regions [112]. The material properties, surface topography, and prosthetic components movements impact the wear mechanisms, steady damage patterns, and implant failures in total knee arthroplasty. The increasing femoral component's surface roughness of total knee prostheses may be a contributing factor to accelerated scratches (wear) observed in the anterior/posterior (AP) direction of all the femoral components and ultimately prosthesis failure [131].

The ceramic-on-ceramic hip implant of the zirconia toughened alumina ceramics is an appropriate replacement material with biocompatibility and low wear. The ceramic-on-ceramic hip implant presents a bone preserving treatment without the metal ion related issues linked with MOM devices [132].

The recent developments in biotribology on implant surfaces are presented in Table 1.11.

1.4.3 Composites

The wear and lubrication of artificial joints are vital concerns for their endurance, durability, and long life. The failure of tibial bearings generally made from ultra-high molecular weight polyethylene (UHMWPE) is due to subsurface fatigue crack commencement and propagation. The fatigue cracks originated in the embrittled oxidized layer in UHMWPE specimens is an unfavorable consequence from sterilization of the tibial bearings [133]. The number of cycles required for fatigue cracks commencement is dependent on the intensity of oxidation and on the contact stress. The implant loosening and ensuing failure leads to vital parameters in the biological response (osteolysis) to the wear debris as shape, size, and number of particles. The clinical hip replacement studies with highly cross-linked polyethylene (XLPE) cups have shown greatly reduced wear (and XLPE wear debris particles) compared with conventional polyethylene (PE) [134]. The reduced wear rate of XLPE should reduce the osteolytic potential, but the reduced debris size may have the possibility to build up the biological activity. The decreased debris size due to cross-linking of UHMWPE can result in greater osteolysis with appropriately large number of generated particles. The capability to provide improved evaluation in-vivo requires an increased understanding of the osteolysis and associated biological processes [134].

The lowest wear rate and friction coefficient of UHMWPE are achieved under human plasma lubrication [135]. The wear mechanism of UHMWPE under (i) dry friction is plastic deformation and adhesive wear, (ii) water lubrication is fatigue fracture wear and severe plowing, and (iii) human plasma lubrication is plastic deformation and fine plowing. The protein serum deposition occurred on worn surface of UHMWPE as the nitrogen content in worn surface areas is much higher than that in unworn surface areas. The main reason for failure of total joint replacements in the long period is the wear of ultra-high molecular weight polyethylene (UHMWPE). The addition of bovine bone hydroxyapatite (BHA) to the UHMWPE composites increases the biocompatibility and wear resistance vital for high quality artificial joints. The BHA/UHMWPE composites under human plasma lubrication conditions reduced the friction coefficient and wear rate, and enhanced the hardness and modulus of elasticity [136]. The ultra-high molecular weight polyethylene (UHMWPE) substrate is treated to augment the adhesion of the hydrogen-containing carbon (HCC) coating [137]. The HCC coating has enhanced wear resistance as a sizable amount of HCC coating remained with the deposited substrate as compared with the polished substrate. The total joint replacements encompass formulation between a metal/alloy and UHMWPE in orthopedic applications. The addition of micro-sized zirconium particles in compression molded ultra-high molecular weight polyethylene (UHMWPE) composites have shown outstanding biocompatibility and substantial reduction in wear compared to conventional UHMWPE [138]. The cross-linking decreases the wear rate of UHMWPE, but brings about reduction in impact toughness. The ultra-high molecular weight polyethylene (UHMWPE) biomaterial is employed as the acetabular cup in artificial hip joints. The main cause of long-term failure of hip joints is the wear debris generation of UHMWPE in human body after their replacements which have demonstrated to induce osteolysis and implant loosening. The natural coral (NC) particles addition in UHMWPE resulted in the enhancement of micro-hardness and scratch resistance of the NC/UHMWPE composites [139]. The NC/UHMWPE composites wear resistance increased with the increasing contents of NC particles. The NC/UHMWPE composites wear mechanism is mainly due to adhesive wear and the NC constituents in UHMWPE altered the adhesive wear severity. The bovine bone hydroxyapatite (BHA) filler is a suitable component to enhance the wear resistance of BHA/UHMWPE composites for biotribological applications [140].

The BHA/UHMWPE composites acetabular cups (obtained by hot pressing formation method) against CoCrMo alloy femoral heads under bovine synovial lubrication can increase the hardness and decrease the wear rates. The principal wear mechanisms for UHMWPE and its composites are adhesive wear, fatigue, and plowing. The major long-term failure identified for metal-on-UHMWPE is implant loosening due to wear generation. The wear progression is simulated taking into consideration Archard's wear model with the finite element simulation of femoral head and acetabular cup [141]. The bearing surface generated under the influence of wear would be beneficial to the hip implant replacement by enhancing the lubricant film and reducing wear. The ultra-high molecular weight polyethylene (UHMWPE) cross-linking without stabilization has potential for the use in biomedical applications with increased bearing wear resistance, yet reduce degradation in stiffness and oxidation resistance [142]. The UHMWPE cross-linking without stabilization revealed a substantial increase in wear resistance yielding a reasonable drop in elastic modulus thus retaining a sizable share of the crystalline polymer original stiffness. The cross-linking followed by thermal stabilization substantially decreased the elastic modulus of UHMWPE, while the thermal stabilization decreased crystallinity more than that obtained without stabilization. The lamellae (crystalline) play an important role in the wear mechanisms and deformation of ultra-high molecular weight polyethylene (UHMWPE) in artificial knee joints [143]. The lamellae (crystalline) under tribologically loaded conditions assemble similar to the alignment of collagen fibrils in natural cartilage. The proposed tribologically loaded UHMWPE model reflects the different depth zones deformations. The stresses which are most influential in modifying the microstructure and are therefore most detrimental to generate wear particles are close by the surfaces subjected to the application of collective large normal loads with high relative velocity. The MWCNT/UHMWPE nanocomposites signify an alluring substitute for the conventional UHMWPE used as bearing surfaces in joint prostheses. The addition of multi-walled carbon nanotubes (MWCNTs) to conventional ultra-high molecular weight polyethylene (UHMWPE) led to a substantial decrease in wear rate in orthopedic applications [144]. The biocompatibility of wear particles from the MWCNT/UHMWPE nanocomposites have been related to decreased implant loosening and osteolysis in comparison to those generated from the conventional UHMWPE. The third-body particle effect on artificially aged vitamin E stabilized polyethylene is a constant wear behavior with effectiveness in oxidation prevention under prolonged artificial aging [109]. The highly cross-linked polyethylene (remelted) has a higher oxidation resistance, whereas standard polyethylene shows oxidative degradation and subsequently increased wear. The highly cross-linked (HXL) UHMWPE blended with vitamin E has superior wear characteristics than that of highly cross-linked (HXL)/conventional UHMWPE (acetabular cups) counterfaced with CoCrMo alloy (femoral head) [145]. The tribological testing of the (i) highly cross-linked (HXL) UHMWPE blended with vitamin E produces surface layer abrasion, (ii) highly cross-linked (HXL) UHMWPE produces surface layer abrasion and flaking facture, and (iii) conventional UHMWPE produces accumulated plastic flow and yielding. The highly cross-linked (HXL) UHMWPE blended with vitamin E can prevent oxidative degradation along with decreasing the surface layer flaking facture occurrence. The Ti6Al4V material comprises an alternate selection to the metal-polymers for total hip arthroplasty (THA) due to high load capacity and good biocompatibility. The Ti6Al4V material contact surfaces display superior levels of preservation and bone transfer by adhesion. The Ti6Al4V material with hydroxyapatite (HAp) and tricalcium phosphate (TCP) is used as metal prostheses coatings owing to the stability of the implants [146]. The biocomposite implant design based on polished surfaces of Ti6Al4V material with hydroxyapatite (HAp) and tricalcium phosphate (TCP) leads to an enhanced primary implant stability. The secondary stability is enhanced due to the adhesion between bone and biocomposite implant, increasing on the whole implant stability [146]. Friction in polyethylene/metal contact pair is significantly affected by protein concentration and sliding speed. The protein content and sliding conditions of polyethylene/metal (UHMWPE/CoCrMo) contact pair have a certain effect on both the structure of the adsorbed molecules and adsorbed film formation and hence affect the friction coefficient [147]. The proteins undergo significant changes in their initial structure complemented by the development of protein film with an increase of friction coefficient. The retrieved UHMWPE tibial implants lead to a key role of third body layer in tribological analysis [148]. The formation of a third body layer composed of a synovial fluid (a Gel-IN calf serum and a calf serum) and UHMWPE wear particles mixture in the implant leads to good tribological performance with a lower wear rate. The Gel-IN calf serum yielded the formation of a third body layer on the UHMWPE surface owing to protein and lipid adsorption which led a lower friction factor [148]. However, the calf serum is unable to attach to the UHMWPE surface which led to a high friction factor. Polyether ether ketone (PEEK) is utilized in arthroplasty along with its composites due of their superior nature. The tribological characteristics of tibia and femur prosthesis contact mode simulation of PEEK against the CoCrMo alloy in torsion under calf serum solution are as follows [149]: (i) the coefficient of friction decreases with increasing torsional angle, and (ii) the wear depth is extended, the wear width is expanded, and wear scars are stretched with an increasing normal load. The PEEK wear mechanism in the central region is plastic deformation, while in the marginal region is mostly due to fatigue and abrasive wear. The ceramic-on-UHMWPE hip replacement implant design enhancement is carried out based on the wear maps displaying the progress of the structure and position of the wear damage [150].

The recent developments in biotribology on implant composites are presented in Table 1.12.

TABLE 1.12
Recent Developments in Biotribology on Implant Composites

Implant composites	Authors
Surface pitting and fatigue cracks in UHMWPE	Kennedy et al. [133]
XLPE implant wear and particles debris	Williams et al. [134]
Tribological behavior of femoral bone against UHMWPE	Wang et al. [135]
BHA filled UHMWPE composites	Liu et al. [136]
HCC coating adhesion enhancement to UHMWPE	Takeichi et al. [137]
Zirconium reinforcement filler particles into UHMWPE	Plumlee et al. [138]
NC reinforcement filler particles into UHMWPE	Ge et al. [139]
BHA/UHMWPE acetabular cups with CoCrMo femoral heads	Wang et al. [140]
Wear simulation prediction of hip joint replacement	Harun et al. [141]
UHMWPE with increased bearing wear resistance	Schwartz & Bahadur [142]
Modeling deformation zones in the UHMWPE sample	Galetz & Glatzel [143]
Tribological behavior of nanocomposite MWCNT/UHMWPE	Suñer et al. [144]
Tribological behavior of artificially aged vitamin E stabilized polyethylene	Grupp et al. [109]
Tribological properties of HXL-UHMWPE/CoCrMo pair	Chen et al. [145]
Tribological properties of metal matrix bioactive composite	Dantas et al. [146]
Adsorbed protein film effect on UHMWPE/ CoCrMo pair	Nečas et al. [147]
Tribological analysis of layered medial knee implants	Sava et al. [148]
Tibia and femur prosthesis contact mode simulation	Liu et al. [149]
Ceramic-on-UHMWPE hip replacements wear map	Mattei et al. [150]

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Zhou Z.R. , Jin Z.M. 2015. Biotribology: recent progresses and future perspectives, Biosurface and Biotribology, 1(1), 3–24.

Smyth P.A. , Green I. 2018. Storage and loss characteristics of coupled poroviscoelastic and hydrodynamic systems for biomimetic applications, The Journal of Tribology, 140(4), 041703.

Jin Z.M. 2006. Theoretical studies of elastohydrodynamic lubrication of artificial hip joints. Proceedings of the IMechE Journal of Engineering Tribology, 220, 719–727.

Klein J. 2006. Molecular mechanisms of synovial joint lubrication, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 220(8), 691–710.

Ateshian G.A. 2009. The role of interstitial fluid pressurization in articular cartilage lubrication, Journal of Biomechanics, 42(9), 1163–1176.

Crockett R. 2009. Boundary lubrication in natural articular joints. Tribology Letters, 35, 77–84.

Mattei L. , DiPuccio F. , Piccigallo B. , Ciulli E. 2011. Lubrication and wear modelling of artificial hip joints: A review, Tribology International, 44, 532–549.

Murakami T. , Yarimitsu S. , Nakashima K. , et al. 2013. Influence of synovia constituents on tribological behaviors of articular cartilage. Friction, 1, 150–162.

Kennedy F.E. , Wongseedakaew K. , McHugh D.J. , Currier J.H. 2013. Tribological conditions in mobile bearing total knee prostheses, Tribology International 63, 78–88.

Myant C. , Cann P. 2014. On the matter of synovial fluid lubrication: implications for metal-on-metal hip tribology, Journal of the Mechanical Behavior of Biomedical Materials 34, 338–348.

Liming S. , Shihao L. , Naohiko S. 2020. Systematic review of computational modelling for biomechanics analysis of total knee replacement, Biosurface and Biotribology, 6(1), 3–11.

Sinha P. , Singh C. , Prasad K.R. 1982. Lubrication of human joints – a microcontinuum approach, Wear 80, 159–181.

Bujurke N.M. , Kudenatti R.B. 2006. An analysis of rough poroealstic bearings with reference to lubrication mechanism of synovial joints, Applied Mathematics and Computation, 178, 309–320.

Mabuchi K. , Ujihira M. , Sasada T. 1998. Relationship between the conformity and the lubricating ability of synovial joints, Clinical Biomechanics, 13(4–5), 250–255.

Jin Z.M. , Dowson D. 2005. Elastohydrodynamic lubrication in biological systems, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 219(5), 367–380.

Ateshian G.A. , Hung C.T. 2006. The natural synovial joint: Properties of cartilage, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 220(8), 657–670.

Pascau A. , Guardia B. , Puertolas J.A. , Gómez-Barrena E. 2009. Knee model of hydrodynamic lubrication during the gait cycle and the infl uence of prosthetic joint conformity, Journal of Orthopaedic Science, 14, 68–75.

Mongkolwongrojn M. , Wongseedakaew K. , Kennedy F.E. 2010. Transient elastohydrodynamic lubrication artificial knee joint with non-Newtonian fluids, Tribology International, 43, 1017–1026.

Ruggiero A. , Gòmez E. , D'Amato R. 2011. Approximate Analytical Model for the Squeeze-Film Lubrication of the Human Ankle Joint with Synovial Fluid Filtrated by Articular Cartilage, Tribology Letters, 41, 337–343.

Ruggiero A. , Gòmez E. , D'Amato R. 2013. Approximate closed form solution of the synovial fluid film force in the human anke joint with non-Newtonian lubricant, Tribology International, 57, 156–161.

Li J. , Stewart T.D. , Jin Z. , Wilcox R.K. , Fishera J. 2013. The influence of size, clearance, cartilage properties, thickness and hemiarthroplasty on the contact mechanics of the hip joint with biphasic layers, The Journal of Biomechanics, 46(10), 1641–1647.

Tanaka K. , Uchijima D. , Hasegawa K. , Katori T. , Sakai R. , Mabuchi K. 2013. Limitation of the lubricating ability of total hip prostheses with hard on hard sliding material, Tribology, 8(5), 272–277.

Abdullah E.Y. , Edan N.M. , Kadhim A.N. 2017. Study Surface Roughness and Friction of Synovial Human Knee Joint with Using Mathematical Model, Special Issue: 1st Scientific International Conference, College of Science, Al-Nahrain University, November, 21–22, Part I, pp. 109–118.

Rao T.V.V.L.N. , Rani A.M.A. , Manivasagam G. 2019. Squeeze film bearing characteristics for synovial joint applications. In: Bains P. , Sidhu S. , Bahraminasab M. , Prakash C. (eds) Biomaterials in Orthopaedics and Bone Regeneration. Materials Horizons: From Nature to

Nanomaterials. Springer, Singapore.
Boedo S. , Coots S.A. 2017. Wear chacteristics of conventional and squeeze-film artificial hip joints, Journal of Tribology, 139, 031603.
Burris D.L. , Moore A.C. 2017. Cartilage and joint lubrication: new insights into the role of hydrodynamics, Biotribology, 12, 8–14.
Horibata S. , Yarimitsu S. , Fujie H. 2018. Influence of synovial fluid pressure on biphasic lubrication property in articular cartilage, Tribology, 13(3), 172–177.
Horibata S. , Yarimitsu S. , Fujie H. 2019. Effect of synovial fluid pressurization on the biphasic lubrication property of articular cartilage, Biotribology, 19, 100098.
Ruggiero A. , Sicilia A. , Affatato S. 2020. In silico total hip replacement wear testing in the framework of ISO 14242-3 accounting for mixed elasto-hydrodynamic lubrication effects, Wear, 460–461, 203420.
Ruggiero A. , Sicilia A. Lubrication modeling and wear calculation in artificial hip joint during the gait, Tribology International 142, 2020, 105993.
Ateshian G.A. , Wang H. , Lai W.M. 1998. The role of interstitial fluid pressurization and surface porosities on the boundary friction of articular cartilage, Journal of Tribology, 120(2), 241–248.
Nakashima K. , Sawae Y. , Murakami T. 2007. Effect of conformational changes and differences of proteins on frictional properties of poly(vinyl alcohol) hydrogel, Tribology International, 40(10–12), 1423–1427.
Yarimitsu S. , Nakashima K. , Sawae Y. , Murakami T. 2009. Influences of lubricant composition on forming boundary film composed of synovia constituents, Tribology International, 42(11–12), 1615–1623.
Pawlak Z. , Figaszewski Z.A. , Gadomski A. , Urbaniak W. , Oloyede A. 2010. The ultra-low friction of the articular surface is pH-dependent and is built on a hydrophobic underlay including a hypothesis on joint lubrication mechanism, Tribology International, 43, 1719–1725.
Pawlak Z. , Yusuf K.Q. , Pai R. , Urbaniak W. 2017. Repulsive surfaces and lamellar lubrication of synovial joints, Archives of Biochemistry and Biophysics, 623–624, 42–48.
Sawano H. , Warisawa S.I. , Ishihara S. 2010. Study on wear reduction mechanism of artificial joints grafted with hydrophilic polymer membranes, Wear 268, 233–240.
Meng Q. , Gao L. , Liu F. , Yang P. , Fisher J. , Jin Z. 2010. Contact mechanics and elastohydrodynamic lubrication in a novel metal-on-metal hip implant with an aspherical bearing surface, Journal of Biomechanics, 43, 849–857.
Vrbka M. , Návrat T. , Křupka I. , Hartl M. , Šperka P. , Gallo J. 2013. Study of film formation in bovine serum lubricated contacts under rolling/sliding conditions, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 227(5), 459–475.
Parkes M. , Myant C. , Cann P.M. , Wong J.S.S. 2015. Synovial fluid lubrication: the effect of protein interactions on adsorbed and lubricating films, Biotribology, 1–2, 51–60.
Boettcher K. , Winkeljann B. , Schmidt T.A. , Lieleg O. 2017. Quantification of cartilage wear morphologies in unidirectional sliding experiments: Influence of different macromolecular lubricants, Biotribology, 12, 43–51.
Murakami T. , Yarimitsu S. , Sakai N. , Nakashima K. , Yamaguchi T. , Sawae Y. 2017. Importance of adaptive multimode lubrication mechanism in natural synovial joints, Tribology International, 113, 306–315.
Nečas D. , Vrbka M. , Křupka I. , Hartl M. , Galandáková A. 2016. Lubrication within hip replacements – Implication for ceramic-on-hard bearing couples, Journal of the Mechanical Behavior of Biomedical Materials, 61, 371–383.
Nečas D. , Vrbka M. , Galandáková A. , Křupka I. , Hartl M. 2019. On the observation of lubrication mechanisms within hip joint replacements. Part I: Hard-on-soft bearing pairs, Journal of the Mechanical Behavior of Biomedical Materials, 89, 237–248.
Nečas D. , Sadecká K. , Vrbka M. , Gall J. , Galandáková A. , Křupka A. , Hartl M. 2019. Observation of lubrication mechanisms in knee replacement: a pilot study, Biotribology, 17, 1–7.
Taufiqurrakhman M. , Bryant M.G. , Neville A. 2019. Tribofilms on CoCrMo alloys: Understanding the role of the lubricant, Biotribology, 19, 100104.
Stevenson H. , Jaggard M. , Akhbari P. , Vaghela U. , Gupte C. , Cann P. 2019. The role of denatured synovial fluid proteins in the lubrication of artificial joints, Biotribology, 17, 49–63.
Wang Z. , Li J. , Ge X. , Liu Y. , Luo J. , Chetwynd D. , Mao K. 2019. Investigation of the lubrication properties and synergistic interaction of biocompatible liposome-polymer complexes applicable to artificial joints, Colloids and Surfaces B: Biointerfaces, 178, 469–478.

Shinmori H. , Kubota M. , Morita T. , Yamaguchi T. , Sawae Y. 2020. Effects of synovial fluid constituents on friction between UHMWPE and CoCrMo, Tribology, 15(4), 283–292.
Cao Y. , Kampf N. , Kosinska M.K. , Steinmeyer J. , Klein J. 2021. Interactions between bilayers of phospholipids extracted from human osteoarthritic synovial fluid, Biotribology, 25, 100157.
Freeman M.E. , Furey M.J. , Love B.J. , Hampton J.M. 2000. Friction, wear, and lubrication of hydrogels as synthetic articular cartilage, Wear, 241(2), 129–135.
Dunn A.C. , Cobb J.A. , Kantzios A.N. , et al. 2008. Friction coefficient measurement of hydrogel materials on living epithelial cells. Tribology Letters, 30, 13.
Bavaresco V.P. , Zavaglia C.A.C. , Reis M.C. , Gomes J.R. 2008. Study on the tribological properties of pHEMA hydrogels for use in artificial articular cartilage, Wear, 265(3–4), 269–277.
Murakami T. , Sawae Y. , Nakashima K. , Yarimitsu S. , Sato T. 2007. Micro- and nanoscopic biotribological behaviours in natural synovial joints and artificial joints, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 221(3), 237–245.
Murakami T. , Nakashima K. , Sawae Y. , Sakai N. , Hosoda N. 2009. Roles of adsorbed film and gel layer in hydration lubrication for articular cartilage, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 223(3), 287–295.
Murakami T. , Nakashima K. , Yarimitsu S. , Sawae Y. , Sakai N. 2011. Effectiveness of adsorbed film and gel layer in hydration lubrication as adaptive multimode lubrication mechanism for articular cartilage, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 225(12), 1174–1185.
Mamada K. , Fridrici V. , Kosukegawa H. , et al. 2011. Friction properties of poly(vinyl alcohol) hydrogel: effects of degree of polymerization and saponification value. Tribol Lett 42, 241–251.
Murakami T. , Yarimitsu S. , Nakashima K. , Yamaguchi T. , Sawae Y. , Sakai N. , Suzuki A. 2014. Superior lubricity in articular cartilage and artificial hydrogel cartilage, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 228(10), 1099–1111.
Murakami T. , Yarimitsu S. , Sakai N. , Nakashima K. , Yamaguchi T. , Sawae Y. , Suzuki A. 2017. Superior lubrication mechanism in poly(vinyl alcohol) hybrid gel as artificial cartilage, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 231(9), 1160–1170.
Yarimitsu S. , Sasaki S. , Murakami T. , Suzuki A. 2016. Evaluation of lubrication properties of hydrogel artificial cartilage materials for joint prosthesis, Biosurface and Biotribology, 2(1), 40–47.
Sardinha V.M. , Lima L.L. , Belangero W.D. , Zavaglia C.A. , Bavaresco V.P. , Gomes J.R. 2013. Tribological characterization of polyvinyl alcohol hydrogel as substitute of articular cartilage, Wear, 301(1–2), 218–225.
Kosukegawa, H. , Fridrici, V. , Kapsa, P. et al. 2013. Friction properties of medical metallic alloys on soft tissue–mimicking poly(vinyl alcohol) hydrogel biomodel. Tribology Letters, 51, 311–321.
Pitenis A.A. , Urueña J.M. , Nixon R.M. , Bhattacharjee T. , Krick B.A. , Dunn A.C. , Angelini T.E. , Sawyer W.G. 2016. Lubricity from entangled polymer networks on hydrogels, The Journal of Tribology, 138(4), 042102.
Cao Y. , Xiong D. , Wang K. , Niu Y. 2017. Semi-degradable porous poly (vinyl alcohol) hydrogel scaffold for cartilage repair: Evaluation of the initial and cell-cultured tribological properties, The Journal of the Mechanical Behavior of Biomedical Materials, 68, 163–172.
Chen K. , Yang X. , Zhang D. , Xu L. , Zhang X. , Wang Q. 2017. Biotribology behavior and fluid load support of PVA/HA composite hydrogel as artificial cartilage, Wear, 376–377(Part A), 329–336.
Kim J. , Dunn A.C. 2018. Thixotropic mechanics in soft hydrated sliding interfaces. Tribology Letters, 66, 102.
Mreła A. , Pawlak Z. 2019. Articular cartilage. Strong adsorption and cohesion of phospholipids with the quaternary ammonium cations providing satisfactory lubrication of natural joints, Biosystems, 176, 27–31.
McGhee E.O. , Urueña J.M. , Pitenis A.A. , et al. 2019. Temperature-dependent friction of gemini hydrogels. Tribology Letters, 67,117.
Sakai N. , Yarimitsu S. , Sawae Y. , Komori M. , Murakami T. 2019. Biomimetic artificial cartilage: fibre-reinforcement of PVA hydrogel to promote biphasic lubrication mechanism, Biosurface and Biotribology, 5(1), 13–19.

Simič R. , Yetkin M. , Zhang K. , et al. 2020. Importance of hydration and surface structure for friction of acrylamide hydrogels. Tribology Letters, 68, 64.
Gan S. , Lin W. , Zou Y. , Xu B. , Zhang X. , Zhao J. , Rong J. 2020. Nano-hydroxyapatite enhanced double network hydrogels with excellent mechanical properties for potential application in cartilage repair, Carbohydrate Polymers, 229, 115523.
Dowson D. , Neville A. 2006. Bio-tribology and bio-mimetics in the operating environment, 220(3), 109–123.
Liu Z. , Yin W. , Tao D. , Tian Y. 2015. A glimpse of superb tribological designs in nature, Biotribology, 1–2, 11–23.
Tang Y.H. , Zhang H.P. 2016. Theoretical understanding of bio-interfaces/bio-surfaces by simulation: A mini review, Biosurface and Biotribology, 2(4), 151–161.
Xie C. 2019. Bio-inspired nanofunctionalisation of biomaterial surfaces: a review, Biosurface and Biotribology, 5(3), 83–92.
Pitenis A.A. , Sawyer W.G. 2020. Soft textured implants: roughness, friction, and the complications, Biotribology, 22, 100127.
Allen Q. , Raeymaekers B. 2021. Surface texturing of prosthetic hip implant bearing surfaces: a review, The Journal of Tribology, 143(4), 040801.
Ito H. , Kaneda K. , Yuhta K. , Nishimura I. , Yasuda K. , Matsuno K. 2000. Reduction of polyethylene wear by concave dimples on the frictional surface in artificial hip joints, The Journal of Arthroplasty, 15(3), 332–338.
Sawano H. , Warisawa S. , Ishihara S. 2009. Study on long life of artificial joints by investigating optimal sliding surface geometry for improvement in wear resistance, Precision Engineering 33, 492–498.
Gao L. , Yang P. , Dymond I. , Fisher J. , Jin Z. 2010. Effect of surface texturing on the elastohydrodynamic lubrication analysis of metal-on-metal hip implants. Tribology International, 43, 1851–1860.
Ghosh S. , Choudhury D. , Roy T. , Mamat A.B. , Masjuki H.H. , Pingguan-Murphy B. 2015. Tribological investigation of diamond-like carbon coated micro-dimpled surface under bovine serum and osteoarthritis oriented synovial fluid, Science and Technology of Advanced Materials, 16, 035002.
Roy T. , Choudhury D. , Ghosha S. , Mamatd A.B. , Pingguan-Murphy B. 2015. Improved friction and wear performance of micro dimpled ceramic-on-ceramic interface for hip joint arthroplasty, Ceramics International, 141, 681–690.
Choudhury D. , Urbana F. , Vrbka M. , Hartla M. , Krupkaa I. 2015. A novel tribological study on DLC-coated micro-dimpled orthopedics implant interface, Journal of the Mechanical Behavior of Biomedical Materials, 45, 121–131.
Choudhury D. , Ghosh S. , Ali F. , Vrbka M. , Hartl M. , Krupka I. 2016. The influence of surface modification on friction and lubrication mechanism under a bovine serum–lubricated condition, Tribology Transactions, 59(2), 316–322.
Choudhury D. , Vrbka M. , Mamat A.B. , Stavness I. , Roy C.K. , Mootanah R. , Krupka I. 2017. The impact of surface and geometry on coefficient of friction of artificial hip joints, Journal of the Mechanical Behavior of Biomedical Materials, 72, 192–199.
Choudhury D. , Rebenda D. , Sasaki S. , Hekrle P. , Vrbka M. , Zou M. 2018. Enhanced lubricant film formation through micro-dimpled hard-on-hard artificial hip joint: An in-situ observation of dimple shape effects, Journal of the Mechanical Behavior of Biomedical Materials, 81, 120–129.
Choudhury D. , Walker R. , Roy T. , Paul S. , Mootanah R. 2013. Performance of honed surface profiles to artificial hip joints: an experimental investigation, International Journal of Precision Engineering and Manufacturing 14(10), 1847–1853.
Choudhury D. , Walker R. , Shirvani A. , Mootanah R. 2013. The influence of honed surfaces on metal-on-metal hip joints, Tribology, 8(3), 195–202.
Qin L. , Lin P. , Zhang Y. , Dong G. , Zeng Q. 2013. Influence of surface wettability on the tribological properties of laser textured Co–Cr–Mo alloy in aqueous bovine serum albumin solution, Applied Surface Science 268, 79–86.
Qiu M. , Chyr A. , Sanders A.P. , Raeymaekers B. 2014. Designing prosthetic knee joints with bio-inspired bearing surfaces, Tribology International, 77, 106–110.
Zhang Y.L. , Zhang X.G. , Matsoukas G. 2015. Numerical study of surface texturing for improving tribological properties of ultra-high molecular weight polyethylene, Biosurface and

Biotribology, 1(4), 270–277.
Menezes P.L. , Kailas S.V. 2016. Role of surface texture and roughness parameters on friction and transfer film formation when UHMWPE sliding against steel, Biosurface and Biotribology, 2(1), 1–10.
Wyatt H. , Elliott M. , Revill P. , Clarke A. 2016. The effect of engineered surface topography on the tribology of CFR-PEEK for novel hip implant materials, Biotribology, 7, 22–30.
Kanda K. , Sato H. , Kinoshita H. , Miyakoshi T. , Kanebako H. , Adachi K. 2016. Influence of surface texture on friction properties of mechanical seals for blood-design concept of sealing surface of mechanical seal for ventricular assist device, Tribology, 11(2), 366–375.
Gao L. , Hua Z. , Hewson R. , Andersen M.S. , Jin Z. 2018. Elastohydrodynamic lubrication and wear modelling of the knee joint replacements with surface topography, Biosurface and Biotribology, 4(1), 18–23.
Allen Q. , Raeymaekers B. 2020. Maximizing the lubricant film thickness between a rigid microtextured and a smooth deformable surface in relative motion, using a soft elasto-hydrodynamic lubrication model, The Journal of Tribology, 142(7), 071802.
Lu Y. , Hua M. , Liu Z. 2014. The biomimetic shark skin optimization design method for improving lubrication effect of engineering surface, The Journal of Tribology, 136(3), 031703.
Zhou Z.R. , Gong W. , Zheng J. 2017. Bionic design perspectives based on the formation echanism of dental anti-wear function, Biosurface and Biotribology, 3(4), 238–244.
Wang Y. 2018. Effect of the bionic morphologies on bio-tribological properties of surface-modified layers on Ti6Al4V with Ni+/N+ implantation, Industrial Lubrication and Tribology, 70(2), 325–330.
Zhong Y. , Zheng L. , Gao Y. , Liu Z. 2019. Numerical simulation and experimental investigation of tribological performance on bionic hexagonal textured surface, Tribology International, 129, 151–161.
Badler D. , Kasem H. 2020. Synergetic effect of the simultaneous use of different biomimetic adhesive micro-structures on tribological performances, Biotribology, 22, 100124.
Quan S. , Yong G. , Jun G. , Liu X. , Yongping J. , Shuyi Y. 2019. Effect of fish scale texture on friction performance for reciprocating pair with high velocity, Industrial Lubrication and Tribology, 72(4), 497–502.
Atwal J.C. , Pandey R.K. 2020. Performance analysis of thrust pad bearing using micro-rectangular pocket and bionic texture, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 235(6), 1232–1250.
Dowson D. 1995. A comparative study of the performance of metallic and ceramic femoral head components in total replacement hip joints, Wear, 190(2), 171–183.
Katta J. , Jin Z. , Ingham E. , Fisher J. 2008. Biotribology of articular cartilage—A review of the recent advances, Medical Engineering & Physics, 30(10), 1349–1363.
Dong H.S. , Qi S.J. 2015. Realising the potential of graphene-based materials for biosurfaces – a future perspective, Biosurface and Biotribology, 1(4), 229–248.
Harper M.L. , Dooris A. , Paré P.E. 2009. The fundamentals of biotribology and its application to spine arthroplasty, SAS Journal, 3(4), 125–132.
Shi S.F.E.L. , Guo Z.G. , Liu W.M. 2015. The recent progress of tribological biomaterials, Biosurface and Biotribology, 1(2), 81–97.
Luo Y. , Chen W. , Tian M. , Teng S. 2015. Thermal oxidation of Ti6Al4V alloy and its biotribological properties under serum lubrication, Tribology International, 89, 67–71.
Grupp T.M. , Holderied M. , Mulliez M.A. , Streller R. , Jäger M. , Blömer W. , Utzschneider S. 2014. Biotribology of a vitamin E-stabilized polyethylene for hip arthroplasty – Influence of artificial ageing and third-body particles on wear, Acta Biomaterialia, 10(7), 3068–3078.
Costa J. , Peixoto J. , Moreira P. , Souto A.P. , Flores P. , Lankarani H.M. 2016. Influence of the hip joint modeling approaches on the kinematics of human gait, The Journal of Tribology, 138(3), 031201.
Ruggiero A. , Merola M. , Affatato S. 2017. On the biotribology of total knee replacement: a new roughness measurements protocol on in vivo condyles considering the dynamic loading from musculoskeletal multibody model, Measurement, 112, 22–28.
Affatato S. , Ruggiero A. , Merola M. , Logozzo S. 2017. Does metal transfer differ on retrieved Biolox® Delta composites femoral heads? Surface investigation on three Biolox® generations from a biotribological point of view, Composites Part B: Engineering, 113, 164–173.

Espallargas N. , Fischer A. , Igual Muñoz A. , Mischler S. , Wimmer M.A. 2017. In-situ generated tribomaterial in metal/metal contacts: Current understanding and future implications for implants, Biotribology, 10, 42–50.
Wang Q. , Ge S. , Zhang D. 2005. Nano-mechanical properties and biotribological behaviors of nanosized HA/partially-stabilized zirconia composites, Wear, 259(7–12), 952–957.
Melero H. , Torrell M. , Fernández J. , Gomes J.R. , Guilemany J.M. 2013. Tribological characterization of biocompatible HAp-TiO2 coatings obtained by high velocity oxy-fuel spray, Wear, 305(1–2), 8–13.
Pettersson M. , Tkachenko S. , Schmidt S. , Berlind T. , Jacobson S. , Hultman L. , Engqvist H. , Persson C. 2013. Mechanical and tribological behavior of silicon nitride and silicon carbon nitride coatings for total joint replacements, Journal of the Mechanical Behavior of Biomedical Materials, 25, 41–47.
Grupp T.M. , Giurea A. , Miehlke R.K. , Hintner M. , Gaisser M. , Schilling C. , Schwiesau J. , Kaddick C. 2013. Biotribology of a new bearing material combination in a rotating hinge knee articulation, Acta Biomaterialia, 9(6), 7054–7063.
Hee A.C. , Zhao Y. , Choudhury D. , Ghosh S. , Zhu Q. , Zhu H. 2016. Tribological behavior of hydrogenated diamond-like carbon on polished alumina substrate with chromium interlayer for biomedical application, Biotribology, 7, 1–10.
Choudhury D. , Morita T. , Sawae Y. , Lackner J.M. , Towler M. , Krupka I. 2016. A novel functional layered diamond like carbon coating for orthopedics applications, Diamond and Related Materials, 61, 56–69.
Choudhury D. , Lackner J. , Fleming R.A. , Goss J. , Chen J. , Zou M. 2017. Diamond-like carbon coatings with zirconium-containing interlayers for orthopedic implants, Journal of the Mechanical Behavior of Biomedical Materials, 68, 51–61.
Han S.X. , Ning Z.W. , Chen K. , Zheng J. 2017. Preparation and tribological properties of Fe-hydroxyapatite bioceramics, Biosurface and Biotribology, 3(2), 75–81.
Xu L. , Zhang D. , Chen K. , Yang X. , Wang Q. , Qi J. 2017. Tribological behavior of diamondlike carbon film-deposited Ti6Al4V alloy swinging against ultrahigh molecular weight polyethylene in fetal bovine serum, The Journal of Tribology, 139(3), 031301.
Qin L. , Feng X. , Hafezi M. , Zhang Y. , Guo J. , Dong G. , Qin Y. 2018. Investigating the tribological and biological performance of covalently grafted chitosan coatings on Co–Cr–Mo alloy, Tribology International, 127, 302–312.
Daavari M. , Atapour M. , Mohedano M. , Arrabal R. , Matykina E. , Taherizadeh A. 2021. Biotribology and biocorrosion of MWCNTs-reinforced PEO coating on AZ31B Mg alloy, Surfaces and Interfaces, 22, 100850.
Ortega-Saenz J.A. , Alvarez-Vera M. , Hernandez-Rodriguez M.A.L. 2013. Biotribological study of multilayer coated metal-on-metal hip prostheses in a hip joint simulator, Wear, 301(1–2), 234–242.
Zhang H. , Zhang S. , Luo J. , Liu Y. , Qian S. , Liang F. , Huang Y. 2013. Investigation of Protein Adsorption Mechanism and Biotribological Properties at Simulated Stem-Cement Interface, The Journal of Tribology 135(3), 032301.
Stevenson H. , Parkes M. , Austin L. , Jaggard M. , Akhbari P. , Vaghela U. , Williams H.R.T. , Gupte C. , Cann P. 2018. The development of a small-scale wear test for CoCrMo specimens with human synovial fluid, Biotribology, 14, 1–10.
Zhang J. , Chen Z. , Gao Y. , Zhang X. , Guo L. , Jin Z. 2019. Computational wear prediction for impact of kinematics boundary conditions on wear of total knee replacement using two cross-shear models, The Journal of Tribology. 141(11), 111201.
Bergiers S. , Hothi H. , Richards R. , Henckel J. , Hart A. 2019. Quantifying the bearing surface wear of retrieved hip replacements, Biosurface and Biotribology, 5(1), 28–33.
Affatato S. , Merola M. , Ruggiero A. 2019. Tribological performances of total knee prostheses: Roughness measurements on medial and lateral compartments of retrieved femoral components, Measurement, 135, 341–347.
Affatato S. , Ruzzi S. , Milosevic M. , Ruggiero A. 2020. Wear characterization and contact surfaces analysis of menisci and femoral retrieved components in bi-condylar knee prostheses, Journal of the Mechanical Behavior of Biomedical Materials, 110, 103959.
de Villiers D. , Collins S. 2020. Wear of large diameter ceramic-on-ceramic hip bearings under standard and microseparation conditions, Biotribology, 21, 100117.

Kennedy F.E. , Currier B.H. , Van Citters D.W. , Currier J.H. , Collier J.P. , Mayor M.B. 2003 Oxidation of ultra-high molecular weight polyethylene and its influence on contact fatigue and pitting of knee bearings, Tribology Transactions, 46(1), 111–118.
Williams P.A. , Yamamoto K. , Masaoka T. , Oonishi H. , Clarke I.C. 2007. Highly crosslinked polyethylenes in hip replacements: improved wear performance or paradox? Tribology Transactions, 50(2), 277–290.
Qing-Liang W. , Ge S. 2007. Comparison of biotribology of swine compact bone against UHMWPE, Journal of China University of Mining and Technology, 17(1), 133–137.
Lie J.-L. , Zhu Y.-Y. , Wang Q.-L. , Ge S. 2008. Biotribological behavior of ultra high molecular weight polyethylene composites containing bovine bone hydroxyapatite, Journal of China University of Mining and Technology, 18(4), 606–612.
Takeichi Y. , Higashiyama T. , Nakahigashi T. , Tanaka Y. , Tsujioka M. , Uemura M. 2008. The effect of sandblasting of UHMWPE substrate on the wear resistance of hydrogen-containing carbon coating, Tribology, 3(2), 94–99.
Plumlee K. , Schwartz C.J. 2009. Improved wear resistance of orthopaedic UHMWPE by reinforcement with zirconium particles, Wear, 267(5–8), 710–717.
Ge S. , Wang S. , Huang X. 2009. Increasing the wear resistance of UHMWPE acetabular cups by adding natural biocompatible particles, Wear, 267(5–8), 770–776.
Wang Q. , Liu J. , Ge S. 2009. Study on biotribological behavior of the combined joint of CoCrMo and UHMWPE/BHA composite in a hip joint simulator, Journal of Bionic Engineering, 6(4), 378–386.
Harun M.N. , Wang F.C. , Jin Z.M. , Fisher J. 2009. Long-term contact-coupled wear prediction for metal-on-metal total hip joint replacement, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 223(7), 993–1001.
Schwartz C.J. , Bahadur S. 2009. Investigation of an Approach to Balance Wear Resistance and Mechanical Properties of Crosslinked UHMWPE. Tribology Letters, 34, 125–131.
Galetz M.C. , Glatzel U. 2010. Molecular deformation mechanisms in UHMWPE during tribological loading in artificial joints. Tribology Letters, 38, 1–13.
Suñer S. , Bladen C.L. , Gowland N. , Tipper J.L. , Emami N. 2014. Investigation of wear and wear particles from a UHMWPE/multi-walled carbon nanotube nanocomposite for total joint replacements, Wear, 317(1–2), 163–169.
Chen G. , Ni Z. , Qian S. , Zhao Y. 2016. Biotribological behaviour of Vitamin E-blended highly cross-linked UHMWPE in a hip joint simulator, Industrial Lubrication and Tribology, 68(5), 548–553.
Dantas T.A. , Abreu C.S. , Costa M.M. , Miranda G. , Silva F.S. , Dourado N. , Gomes J.R. 2017. Bioactive materials driven primary stability on titanium biocomposites, Materials Science and Engineering: C, 77, 1104–1110.
Nečas D. , Sawae Y. , Fujisawa T. , Nakashima K. , Morita T. , Yamaguchi T. , Vrbka M. , Křupka I. , Hartl M. 2017. The influence of proteins and speed on friction and adsorption of metal/UHMWPE contact pair, Biotribology, 11, 51–59.
Sava M.M. , Munteanu B. , Renault E. , Berthier Y. , Trunfio-Sfarghiu A.M. 2018. Tribological analysis of UHMWPE tibial implants in unicompartmental knee replacements: from retrieved to in vitro studies, Biotribology, 13, 1–15.
Liu D. , Wang Q. , Zhang D. , Wang J. , Zhang X. 2019. Torsional friction behavior of contact interface between PEEK and CoCrMo in Calf Serum, Journal of Tribology, 141(1), 011602.
Mattei L. , Di Puccio F. , Ciulli E. , Pauschitz A. 2020. Experimental investigation on wear map evolution of ceramic-on-UHMWPE hip prosthesis, Tribology International, 143, 106068.

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Kurtz, S. , K. Ong , E. Lau , F. Mowat , and M. Halpern . 2007. “Projections of Primary and Revision Hip and Knee Arthroplasty in the United States from 2005 to 2030”. The Journal of Bone & Joint Surgery, 89 (4): 780–785. doi:10.2106/JBJS.F.00222.
Price, A.J. , A. Alvand , A. Troelsen , J.N. Katz , G. Hooper , A. Gray , A. Carr , and D. Beard . 2018. “Knee Replacement”. The Lancet 392 (10158): 1672–1682. doi:10.1016/S0140-6736(18)32344-4.

Evans, J.T. , J.P. Evans , R.W. Walker , A.W. Blom , M.R. Whitehouse , and A. Sayers . 2019. “How Long Does a Hip Replacement Last? A Systematic Review and Meta-Analysis of Case Series and National Registry Reports with More than 15 Years of Follow-Up”. The Lancet 393 (10172): 647–654. doi:10.1016/S0140-6736(18)31665-9.
Cook, R. , P. Davidson , and R. Martin . “More Than 80% of Total Knee Replacements Can Last for 25 Years”. BMJ. doi:10.1136/bmj.l5680.
Inacio, M.C.S. , E.W. Paxton , S.E. Graves , R.S. Namba , and S. Nemes . 2017. “Projected Increase in Total Knee Arthroplasty in the United States – An Alternative Projection Model”. Osteoarthritis and Cartilage 25 (11): 1797–1803. doi:10.1016/j.joca.2017.07.022.
Gallo, J. , S.B. Goodman , Y.T. Konttinen , M.A. Wimmer , and M. Holinka . 2013. “Osteolysis around Total Knee Arthroplasty: A Review of Pathogenetic Mechanisms”. Acta Biomaterialia 9 (9): 8046–8058. doi:10.1016/j.actbio.2013.05.005.
Jin, Z.M. , M. Stone , E. Ingham , and J. Fisher . 2006. “(V) Biotribology”. Current Orthopaedics 20 (1): 32–40. doi:10.1016/j.cuor.2005.09.005.
Serro, A.P. , K. Degiampietro , R. Colaço , and B. Saramago . 2010. “Adsorption of Albumin and Sodium Hyaluronate on Uhmwpe: A Qcm-D and Afm Study”. Colloids and Surfaces B: Biointerfaces 78 (1): 1–7. doi:10.1016/j.colsurfb.2010.01.022.
Ruggiero, A. 2020. “Milestones in Natural Lubrication of Synovial Joints”. Frontiers in Mechanical Engineering 6 (July). doi:10.3389/fmech.2020.00052.
Scholes, S.C. , A. Unsworth , and A.A.J. Goldsmith . 2000. “A Frictional Study of Total Hip Joint Replacements”. Physics in Medicine and Biology 45 (12): 3721–3735. doi:10.1088/0031-9155/45/12/315.
Dowson, D. , and Z.-M. Jin . 2006. “Metal-On-Metal Hip Joint Tribology”. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 220 (2): 107–118. doi:10.1243/095441105X69114.
Albahrani, S.M.B. , D. Philippon , P. Vergne , and J.M. Bluet . 2015. “A Review of In Situ Methodologies for Studying Elastohydrodynamic Lubrication”. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 230 (1): 86–110. doi:10.1177/1350650115590428.
Dowson, D. , C.M. McNie , and A.A.J. Goldsmith . 2000. “Direct Experimental Evidence Of Lubrication In A Metal-On-Metal Total Hip Replacement Tested In A Joint Simulator”. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 214 (1): 75–86. doi:10.1243/0954406001522822.
Smith, S.L. , D. Dowson , A.A.J. Goldsmith , R. Valizadeh , and J.S. Colligon . 2001. “Direct Evidence of Lubrication in Ceramic-On-Ceramic Total Hip Replacements”. Proceedings of the Institution of Mechanical Engineers, Part C: Journal Of Mechanical Engineering Science 215 (3): 265–268. doi:10.1243/0954406011520706.
Smith, S.L. , D. Dowson , and A.A.J. Goldsmith . 2001. “The Effect of Femoral Head Diameter Upon Lubrication and Wear of Metal-On-Metal Total Hip Replacements”. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 215 (2): 161–170. doi:10.1243/0954411011533724.
Smith, S.L. , D. Dowson , and A.A.J. Goldsmith . 2006. “The Effect of Diametral Clearance, Motion and Loading Cycles Upon Lubrication of Metal-On-Metal Total Hip Replacements”. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 215 (1): 1–5. doi:10.1243/0954406011520454.
Brockett, C.L. , P. Harper , S. Williams , G.H. Isaac , R.S. Dwyer-Joyce , Z. Jin , and J. Fisher . 2008. “The Influence of Clearance on Friction, Lubrication and Squeaking in Large Diameter Metal-On-Metal Hip Replacements”. Journal of Materials Science: Materials in Medicine 19 (4): 1575–1579. doi:10.1007/s10856-007-3298-9.
Nečas, D. , M. Vrbka , F. Urban , J. Gallo , I. Křupka , and M. Hartl . 2017. “In Situ Observation of Lubricant Film Formation in THR Considering Real Conformity: The Effect of Diameter, Clearance and Material”. Journal of the Mechanical Behavior of Biomedical Materials 69: 66–74. doi:10.1016/j.jmbbm.2016.12.018.
Medley, J.B. 2016. “Can Physical Joint Simulators Be Used to Anticipate Clinical Wear Problems of New Joint Replacement Implants Prior to Market Release?”. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 230 (5): 347–358. doi:10.1177/0954411916643902.
Fisher, J. 2011. “Bioengineering Reasons for the Failure of Metal-On-Metal Hip Prostheses”. The Journal of Bone and Joint Surgery. British Volume 93-B (8): 1001–1004. doi:10.1302/0301-

620X.93B8.26936.
Mavraki, A. and P.M. Cann . 2009. “Friction and Lubricant Film Thickness Measurements on Simulated Synovial Fluids”. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 223 (3): 325–335. doi:10.1243/13506501JET580.
Mavraki, A. , and P.M. Cann . 2011. “Lubricating Film Thickness Measurements with Bovine Serum”. Tribology International 44 (5): 550–556. doi:10.1016/j.triboint.2010.07.008.
Myant, C. , R. Underwood , J. Fan , and P.M. Cann . 2012. “Lubrication of Metal-On-Metal Hip Joints: The Effect of Protein Content and Load on Film Formation and Wear”. Journal of the Mechanical Behavior of Biomedical Materials 6: 30–40. doi:10.1016/j.jmbbm.2011.09.008.
Myant, C. , and P. Cann . 2013. “In Contact Observation of Model Synovial Fluid Lubricating Mechanisms”. Tribology International 63: 97–104. doi:10.1016/j.triboint.2012.04.029.
Shinmori, H. , M. Kubota , T. Morita , T. Yamaguchi , and Y. Sawae . 2020. “Effects of Synovial Fluid Constituents on Friction between UHMWPE and CoCcrMo”. Tribology Online 15 (4): 283–292. doi:10.2474/trol.15.283.
Vrbka, M. , T. Návrat , I. Křupka , M. Hartl , P. Šperka , and J. Gallo . 2013. “Study of Film Formation in Bovine Serum Lubricated Contacts under Rolling/Sliding Conditions”. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 227 (5): 459–475. doi:10.1177/1350650112471000.
Myant, C.W. , and P. Cann . 2014. “The Effect of Transient Conditions on Synovial Fluid Protein Aggregation Lubrication”. Journal of the Mechanical Behavior of Biomedical Materials 34: 349–357. doi:10.1016/j.jmbbm.2014.02.005.
Myant, C. , and P. Cann . 2014. “On the Matter of Synovial Fluid Lubrication: Implications for Metal-On-Metal Hip Tribology”. Journal of the Mechanical Behavior of Biomedical Materials 34: 338–348. doi:10.1016/j.jmbbm.2013.12.016.
Vrbka, M. , I. Křupka , M. Hartl , T. Návrat , J. Gallo , and A. Galandáková . 2014. “In Situ Measurements of Thin Films In Bovine Serum Lubricated Contacts Using Optical Interferometry”. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 228 (2): 149–158. doi:10.1177/0954411913517498.
Vrbka, M. , D. Nečas , M. Hartl , I. Křupka , F. Urban , and J. Gallo . 2015. “Visualization of Lubricating Films between Artificial Head and Cup With Respect to Real Geometry”. Biotribology 1–2: 61–65. doi:10.1016/j.biotri.2015.05.002.
Nečas, D. , M. Vrbka , D. Rebenda , J. Gallo , A. Galandáková , L. Wolfová , I. Křupka , and M. Hartl . 2018. “In Situ Observation of Lubricant Film Formation in THR Considering Real Conformity: The Effect of Model Synovial Fluid Composition”. Tribology International 117: 206–216. doi:10.1016/j.triboint.2017.09.001.
Choudhury, D. , D. Rebenda , S. Sasaki , P. Hekrle , M. Vrbka , and M. Zou . 2018. “Enhanced Lubricant Film Formation through Micro-Dimpled Hard-On-Hard Artificial Hip Joint: An In-Situ Observation of Dimple Shape Effects”. Journal of the Mechanical Behavior of Biomedical Materials 81: 120–129. doi:10.1016/j.jmbbm.2018.02.014.
Nečas, D. , M. Vrbka , F. Urban , I. Křupka , and M. Hartl . 2016. “The Effect of Lubricant Constituents on Lubrication Mechanisms in Hip Joint Replacements”. Journal of the Mechanical Behavior of Biomedical Materials 55: 295–307. doi:10.1016/j.jmbbm.2015.11.006.
Nečas, D. , M. Vrbka , I. Křupka , M. Hartl , and A. Galandáková . 2016.“Lubrication within Hip Replacements – Implication for Ceramic-On-Hard Bearing Couples”. Journal of the Mechanical Behavior of Biomedical Materials 61: 371–383. http://dx.doi.org/10.1016/j.jmbbm.2016.04.003.
Nečas, D. , M. Vrbka , A. Galandáková , I. Křupka , and M. Hartl . 2019. “On The Observation of Lubrication Mechanisms within Hip Joint Replacements. Part I: Hard-On-Soft Bearing Pairs”. Journal of the Mechanical Behavior of Biomedical Materials 89: 237–248. doi:10.1016/j.jmbbm.2018.09.022.
Nečas, D. , M. Vrbka , J. Gallo , I. Křupka , and M. Hartl . 2019. “On the Observation of Lubrication Mechanisms within Hip Joint Replacements. Part II: Hard-On-Hard Bearing Pairs”. Journal of the Mechanical Behavior of Biomedical Materials 89: 249–259. doi:10.1016/j.jmbbm.2018.09.026.
Murakami, T. , and N. Ohtsuki . 1987. “Paper Xii(Iii) Lubricating Film Formation In Knee Prostheses Under Walking Conditions”. *In* Fluid Film Lubrication – Osborne Reynolds Centenary, Proceedings of the 13Th Leeds–Lyon Symposium on Tribology, Held In Bodington Hall, The University Of Leeds, 387–392. Tribology Series. Elsevier. doi:10.1016/S0167-8922(08)70968-4.

Sawae, Y. , T. Murakami , H. Higaki , and S. Moriyama . 1996. “Lubrication Property of Total Knee Prostheses with PVA Hydrogel Layer as Artificial Cartilage”. JSME International Journal. Ser. C, Dynamics, Control, Robotics, Design And Manufacturing 39 (2): 356–364. doi:10.1299/jsmec1993.39.356.

Ohtsuki, N. , T. Murakami , S. Moriyama , and H. Higaki . 1997. “Influence of Geometry of Conjunction on Elastohydrodynamic Film Formation in Knee Prostheses with Compliant Layer”. In Elastohydrodynamics – ’96 Fundamentals And Applications In Lubrication And Traction, Proceedings of the 23Rd Leeds-Lyon Symposium on Tribology Held in the Institute of Tribology, Department of Mechanical Engineering, 349–359. Tribology Series. Elsevier. doi:10.1016/S0167-8922(08)70464-4.

Flannery, M. , E. Jones , and C. Birkinshaw . 2008. “Analysis of Wear And Friction of Total Knee Replacements Part Ii: Friction and Lubrication as a Function of Wear”. Wear 265 (7–8): 1009–1016. doi:10.1016/j.wear.2008.02.023.

Nečas, D. , K. Sadecká , M. Vrbka , J. Gallo , A. Galandáková , I. Křupka , and M. Hartl . 2019. “Observation of Lubrication Mechanisms in Knee Replacement: A Pilot Study”. Biotribology 17: 1–7. doi:10.1016/j.biotri.2019.02.001.

Nečas, D. , K. Sadecká , M. Vrbka , A. Galandáková , M.A. Wimmer , J. Gallo , and M. Hartl . 2021. “The Effect of Albumin and Γ-Globulin on Synovial Fluid Lubrication: Implication for Knee Joint Replacements”. Journal of the Mechanical Behavior of Biomedical Materials 113. doi:10.1016/j.jmbbm.2020.104117.

Nečas, D. , M. Vrbka , M. Marian , B. Rothammer , S. Tremmel , S. Wartzack , A. Galandáková , J. Gallo , M.A. Wimmer , I. Křupka , and M. Hartl , 2021. “Towards the Understanding of Lubrication Mechanisms in Total Knee Replacements – Part I: Experimental Investigations”. Tribology International 156: 1–13. doi:10.1016/j.triboint.2021.106874.

Goenka, P.K. , and J.F. Booker . 1980. “Spherical Bearings: Static and Dynamic Analysis via the Finite Element Method.” Journal of Lubrication Technology 102 (3): 308–318. doi:10.1115/1.3251522.

Jin, Z.M. , and D. Dowson . 1999. “A Full Numerical Analysis of Hydrodynamic Lubrication in Artificial Hip Joint Replacements Constructed from Hard Materials.” Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 213 (4): 355–370. doi:10.1243/0954406991522310.

Meyer, D.M. , and J.A. Tichy . 2003. “3-D Model of a Total Hip Replacement in Vivo Providing Hydrodynamic Pressure and Film Thickness for Walking and Bicycling.” Journal of Biomechanical Engineering 125 (6): 777–784. doi:10.1115/1.1631585.

Pascau, A. , B. Guardia , J.A. Puertolas , and E. Gómez-Barrena . 2009. “Knee Model of Hydrodynamic Lubrication during the Gait Cycle and the Influence of Prosthetic Joint Conformity.” Journal of Orthopaedic Science: Official Journal of the Japanese Orthopaedic Association 14 (1): 68–75. doi:10.1007/s00776-008-1287-6.

Jin, Z.M. , D. Dowson , and J. Fisher . 1997. “Analysis of Fluid Film Lubrication in Artificial Hip Joint Replacements with Surfaces of High Elastic Modulus”. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 211 (3): 247–256. doi:10.1243/0954411971534359.

Jin, Z.M. , D. Dowson , J. Fisher , N. Ohtsuki , T. Murakami , H. Higaki , and S. Moriyama . 1998. “Prediction of Transient Lubricating Film Thickness in Knee Prostheses with Compliant Layers.” Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine 212 (3): 157–164. doi:10.1243/0954411981533935.

Marian, M. , M. Bartz , S. Wartzack , and A. Rosenkranz . 2020a. “Non-Dimensional Groups, Film Thickness Equations and Correction Factors for Elastohydrodynamic Lubrication: A Review.” Lubricants 8 (10): 95. doi:10.3390/lubricants8100095.

Hamrock, B.J. , and D. Dowson . 1978. “Elastohydrodynamic Lubrication of Elliptical Contacts for Materials of Low Elastic Modulus I—Fully Flooded Conjunction.” Journal of Lubrication Technology 100 (2): 236–245. doi:10.1115/1.3453152.

Jin, Z.M. , D. Dowson , and J. Fisher . 1993. “Fluid Film Lubrication in Natural Hip Joints.” In Thin Films in Tribology, Proceedings of the 19th Leeds-Lyon Symposium on Tribology Held at the Institute of Tribology, University of Leeds 25: 545–555. Tribology Series: Elsevier.

Reynolds, O. 1886. “On the Theory of Lubrication and Its Application to Mr. Beauchamp Tower’s Experiments, Including an Experimental Determination of the Viscosity of Olive Oil.” Philosophical Transactions of the Royal Society of London 177: 157–234.

Cross, M.M. 1965. “Rheology of Non-Newtonian Fluids: A New Flow Equation for Pseudoplastic Systems.” Journal of Colloid Science 20 (5): 417–437. doi:10.1016/0095-8522(65)90022-X.
Carreau, P.J. 1972. “Rheological Equations from Molecular Network Theories.” Transactions of the Society of Rheology 16 (1): 99–127. doi:10.1122/1.549276.
Mattei, L. , F. Di Puccio , B. Piccigallo , and E. Ciulli . 2011. “Lubrication and Wear Modelling of Artificial Hip Joints: A Review.” Tribology International 44 (5): 532–549. doi:10.1016/j.triboint.2010.06.010.
Jalali-Vahid, D. , M. Jagatia , Z.M. Jin , and D. Dowson . 2000. “Elastohydrodynamic Lubrication Analysis of UHMWPE Hip Joint Replacements.” In Thinning Films and Tribological Interfaces, Proceedings of the 26th Leeds-Lyon Symposium on Tribology. Vol. 38, 329–339. Tribology Series: Elsevier.
Jalali-Vahid, D. , M. Jagatia , Z.M. Jin , and D. Dowson . 2001. “Prediction of Lubricating Film Thickness in a Ball-In-Socket Model with a Soft Lining Representing Human Natural And Artificial Hip Joints”. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 215 (4): 363–372. doi:10.1243/1350650011543600.
Jalali-Vahid, D. , M. Jagatia , Z.M. Jin , and D. Dowson . 2001. “Prediction of Lubricating Film Thickness in Uhmwpe Hip Joint Replacements”. Journal of Biomechanics 34 (2): 261–266. doi:10.1016/S0021-9290(00)00181-0.
Jalali-Vahid, D. , and Z.M. Jin . 2001. “Transient Elastohydrodynamic Lubrication Analysis of Ultra-High Molecular Weight Polyethylene Hip Joint Replacements.” Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 216 (4): 409–420. doi:10.1243/0954406021525205.
Jalali-Vahid, D. , Z.M. Jin , and D. Dowson . 2003a. “Elastohydrodynamic Lubrication Analysis of Hip Implants with Ultra High Molecular Weight Polyethylene Cups under Transient Conditions.” Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 217 (7): 767–777. doi:10.1243/095440603767764417.
Wang, F.C. , and Z.M. Jin . 2004. “Prediction of Elastic Deformation of Acetabular Cups and Femoral Heads for Lubrication Analysis of Artificial Hip Joints.” Proceedings of the IMechE 218 (3): 201–209. doi:10.1243/1350650041323331.
Wang, F.C. , and Z.M. Jin . 2005. “Elastohydrodynamic Lubrication Modeling of Artificial Hip Joints under Steady-State Conditions”. Journal of Tribology 127 (4): 729–739. doi:10.1115/1.1924460.
Jagatia, M. , and Z.M. Jin . 2001. “Elastohydrodynamic Lubrication Analysis of Metal-on-Metal Hip Prostheses under Steady State Entraining Motion.” Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine 215 (6): 531–541. doi:10.1243/0954411011536136.
Wang, D. 1994. “Elastohydrodynamic Lubrication of Point Contacts for Layers of ‘Soft’ Solids and for ‘Monolithic’ ‘Hard’ Materials in the Transient Bouncing Ball Problem.” PhD Thesis, University of Leeds, UK. https://books.google.de/books?id=MM05vwEACAAJ.
Udofia, I.J. , and Z.M. Jin . 2003. “Elastohydrodynamic Lubrication Analysis of Metal-on-Metal Hip-Resurfacing Prostheses.” Journal of Biomechanics 36 (4): 537–544. doi:10.1016/S0021-9290(02)00422-0.
Wang, W.-Z. , F.-C. Wang , Z.-M. Jin , D. Dowson , and Y.-Z. Hu . 2009. “Numerical Lubrication Simulation of Metal-on-Metal Artificial Hip Joint Replacements: Ball-in-Socket Model and Ball-on-Plane Model.” Proceedings of the IMechE 223 (7): 1073–1082. doi:10.1243/13506501JET581.
Jalali-Vahid, D. , Z.M. Jin , and D. Dowson . 2003. “Isoviscous Elastohydrodynamic Lubrication of Circular Point Contacts with Particular Reference to Metal-on-Metal Hip Implants.” Proceedings of the IMechE 217 (5): 397–402. doi:10.1243/135065003322445313.
Williams, S. , D. Jalali-Vahid , C. Brockett , Z. Jin , M.H. Stone , E. Ingham , and J. Fisher . 2006. “Effect of Swing Phase Load on Metal-on-Metal Hip Lubrication, Friction and Wear.” Journal of Biomechanics, 2274–2281. doi:10.1016/j.jbiomech.2005.07.011.
Jalali-Vahid, D , Z.M. Jin , and D. Dowson . 2006. “Effect of Start-up Conditions on Elastohydrodynamic Lubrication of Metal-on-Metal Hip Implants.” Proceedings of the IMechE 220 (3): 143–150. doi:10.1243/13506501JET150.
Wang, F. , and Z. Jin . 2008. “Transient Elastohydrodynamic Lubrication of Hip Joint Implants.” Journal of Tribology Transaction of ASME 130 (1). doi:10.1115/1.2806200.
Liu, F. , Z. Jin , P. Roberts , and P. Grigoris . 2007. “Effect of Bearing Geometry and Structure Support on Transient Elastohydrodynamic Lubrication of Metal-on-Metal Hip Implants.” Journal

of Biomechanics, 1340–1349. doi:10.1016/j.jbiomech.2006.05.015.
Liu, F. , Z.M. Jin , F. Hirt , C. Rieker , P. Roberts , and P. Grigoris . 2005. "Effect of Wear of Bearing Surfaces on Elastohydrodynamic Lubrication of Metal-on-Metal Hip Implants." Proceedings of the Institution of Mechanical Engineers. Part H, Journal of engineering in medicine 219 (5): 319–328. doi:10.1243/095441105X34356.
Liu, F. , Z. Jin , P. Roberts , and P. Grigoris . 2006. "Importance of Head Diameter, Clearance, and Cup Wall Thickness in Elastohydrodynamic Lubrication Analysis of Metal-on-Metal Hip Resurfacing Prostheses." Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine 220 (6): 695–704. doi:10.1243/09544119JEIM172.
Wang, F.C. , and Z.M. Jin . 2007. "Effect of Non-Spherical Bearing Geometry on Transient Elastohydrodynamic Lubrication in Metal-on-Metal Hip Joint Implants." Proceedings of the IMechE 221 (3): 379–389. doi:10.1243/13506501JET249.
Wang, F.C. , S.X. Zhao , A.F. Quiñonez , H. Xu , X.S. Mei , and Z.M. Jin . 2009. "Nonsphericity of Bearing Geometry and Lubrication in Hip Joint Implants." Journal of Tribology Transactions of ASME 131 (3). doi:10.1115/1.3118782.
Gao, L. , P. Yang , I. Dymond , J. Fisher , and Z. Jin . 2010. "Effect of Surface Texturing on the Elastohydrodynamic Lubrication Analysis of Metal-on-Metal Hip Implants." Tribology International 43 (10): 1851–1860. doi:10.1016/j.triboint.2010.02.006.
Hu, Y.-Z. , and D. Zhu . 2000. "A Full Numerical Solution to the Mixed Lubrication in Point Contacts." Journal of Tribology 122 (1): 1. doi:10.1115/1.555322.
Gao, L.M. , Q.E. Meng , F. Liu , J. Fisher , and Z.M. Jin . 2010. "The Effect of Aspherical Geometry and Surface Texturing on the Elastohydrodynamic Lubrication of Metal-on-Metal Hip Prostheses under Physiological Loading and Motions." Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 224 (12): 2627–2636. doi:10.1243/09544062JMES2193.
Gao, L.M. , Q.E. Meng , F.C. Wang , P.R. Yang , and Z.M. Jin . 2007. "Comparison of Numerical Methods for Elastohydrodynamic Lubrication Analysis of Metal-on-Metal Hip Implants: Multi-Grid Verses Newton-Raphson." Proceedings of the IMechE 221 (2): 133–140. doi:10.1243/13506501JET228.
Gao, L. , F. Wang , P. Yang , and Z. Jin . 2009. "Effect of 3D Physiological Loading and Motion on Elastohydrodynamic Lubrication of Metal-on-Metal Total Hip Replacements." Medical Engineering & Physics 31 (6): 720–729. doi:10.1016/j.medengphy.2009.02.002.
Venner, C.H. , and A.A. Lubrecht . 2000. Multilevel Methods in Lubrication. 1. Auflage. Amsterdam: Elsevier.
Mattei, L. , B. Piccigallo , K. Stadler , E. Ciulli , and F. Di Puccio . 2009. "EHL Modeling of Hip Implants Based on a Ball-on-Plane Configuration." Ancona, Italy: AIMETA, 161–173.
Gao, L. , J. Fisher , and Z. Jin . 2011. "Effect of Walking Patterns on the Elastohydrodynamic Lubrication of Metal-on-Metal Total Hip Replacements." Proceedings of the IMechE 225 (6): 515–525. doi:10.1177/1350650110396802.
Meng, Q.E. , F. Liu , J. Fisher , and Z.M. Jin . 2011. "Transient Elastohydrodynamic Lubrication Analysis of a Novel Metal-on-Metal Hip Prosthesis with a Non-Spherical Femoral Bearing Surface." Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine 225 (1): 25–37. doi:10.1243/09544119JEIM795.
Meng, Q. , F. Liu , J. Fisher , and Z. Jin . 2013. "Contact Mechanics and Lubrication Analyses of Ceramic-on-Metal Total Hip Replacements." Tribology International 63: 51–60. doi:10.1016/j.triboint.2012.02.012.
Yao, J.Q. , M.P. Laurent , T.S. Johnson , C.R. Blanchard , and R.D. Crowninshield . 2003. "The Influences of Lubricant and Material on Polymer/CoCr Sliding Friction." Wear 255 (1–6): 780–784. doi:10.1016/S0043-1648(03)00180-7.
Wang, W.-Z. , Z.M. Jin , D. Dowson , and Y.Z. Hu . 2008. "A Study of the Effect of Model Geometry and Lubricant Rheology upon the Elastohydrodynamic Lubrication Performance of Metal-on-Metal Hip Joints." Proceedings of the IMechE 222 (3): 493–501. doi:10.1243/13506501JET363.
Gao, L. , D. Dowson , and R.W. Hewson . 2016. "A Numerical Study of Non-Newtonian Transient Elastohydrodynamic Lubrication of Metal-on-Metal Hip Prostheses." Tribology International 93: 486–494. doi:10.1016/j.triboint.2015.03.003.
Wang, F.C. , C. Brockett , S. Williams , I. Udofia , J. Fisher , and Z.M. Jin . 2008. "Lubrication and Friction Prediction in Metal-on-Metal Hip Implants." Physics in Medicine and Biology, 53 (5): 1277–1293. doi:10.1088/0031-9155/53/5/008.

Gao, L. , D. Dowson , and R.W. Hewson . 2017. “Predictive Wear Modeling of the Articulating Metal-on-Metal Hip Replacements.” Journal of Biomedical Materials Research. Part B, Applied Biomaterials 105 (3): 497–506. doi:10.1002/jbm.b.33568.

Gao, L. , Z. Hua , and R. Hewson . 2018. “Can a “Pre-Worn” Bearing Surface Geometry Reduce the Wear of Metal-on-Metal Hip Replacements? – a Numerical Wear Simulation Study.” Wear 406–407: 13–21. doi:10.1016/j.wear.2018.03.010.

Liu, F. , J. Fisher , and Z. Jin . 2013. “Effect of Motion Inputs on the Wear Prediction of Artificial Hip Joints.” Tribology International 63: 105–114. doi:10.1016/j.triboint.2012.05.029.

Ruggiero, A. , A. Sicilia , and S. Affatato . 2020. “In Silico Total Hip Replacement Wear Testing in the Framework of ISO 14242-3 Accounting for Mixed Elasto-Hydrodynamic Lubrication Effects.” Wear 460–461: 203420. doi:10.1016/j.wear.2020.203420.

Ruggiero, A. , and A. Sicilia . 2020. “Lubrication Modeling and Wear Calculation in Artificial Hip Joint During the Gait.” Tribology International 142: 105993. doi:10.1016/j.triboint.2019.105993.

Ruggiero, A. , and A. Sicilia . 2020. “A Mixed Elasto-Hydrodynamic Lubrication Model for Wear Calculation in Artificial Hip Joints.” Lubricants 8 (7): 72. doi:10.3390/lubricants8070072.

Meng, Q. 2010. “Elastohyrodynamic Lubrication in Metal-on-Metal Artificial Hip Joints with Aspherical Bearing Surfaces and Complex Structures.” PhD thesis, University of Leeds.

Dowson, D. , C. Hardaker , M. Flett , and G.H. Isaac . 2004. “A Hip Joint Simulator Study of the Performance of Metal-on-Metal Joints: Part II: Design.” The Journal of Arthroplasty 19 (8 Suppl 3): 124–130. doi:10.1016/j.arth.2004.09.016.

Lu, X. , D. Nečas , Q. Meng , D. Rebenda , M. Vrbka , M. Hartl , and Z. Jin . 2020. “Towards the Direct Validation of Computational Lubrication Modelling of Hip Replacements.” Tribology International 146: 106240. doi:10.1016/j.triboint.2020.106240.

Tandon, P.N. , and S. Jaggi . 1979. “A Model for the Lubrication Mechanism in Knee Joint Replacements.” Wear 52 (2): 275–284. doi:10.1016/0043-1648(79)90068-1.

Kennedy, F.E. , D.W. van Citters , K. Wongseedakaew , and M. Mongkolwongrojn . 2007. “Lubrication and Wear of Artificial Knee Joint Materials in a Rolling⁄Sliding Tribotester.” Journal of Tribology 129 (2): 326. doi:10.1115/1.2464130.

Mongkolwongrojn, M. , K. Wongseedakaew , and F.E. Kennedy . 2010. “Transient Elastohydrodynamic Lubrication in Artificial Knee Joint with Non-Newtonian Fluids.” Tribology International 43 (5–6): 1017–1026. doi:10.1016/j.triboint.2009.12.041.

Su, Y. , Z. Fu , P. Yang , and C. Wang . 2010. “A Full Numerical Analysis of Elastohydrodynamically Lubrication in Knee Prosthesis under Walking Condition.” Journal of Mechanics in Medicine and Biology 10 (4): 621–641. doi:10.1142/S0219519410003605.

Su, Y. , P. Yang , Z. Fu , Z. Jin , and C. Wang . 2011. “Time-Dependent Elastohydrodynamic Lubrication Analysis of Total Knee Replacement under Walking Conditions.” Computer Methods in Biomechanics and Biomedical Engineering 14 (6): 539–548. doi:10.1080/10255842.2010.485569.

Gao, L. , Z. Hua , R. Hewson , M.S. Andersen , and Z. Jin . 2018. “Elastohydrodynamic Lubrication and Wear Modelling of the Knee Joint Replacements with Surface Topography.” Biosurface and Biotribology 4 (1): 18–23. doi:10.1049/bsbt.2017.0003.

Marian, M. , C. Orgeldinger , B. Rothammer , D. Nečas , M. Vrbka , I. Křupka , M. Hartl , M.A. Wimmer , S. Tremmel , and S. Wartzack . 2020b. “Towards the Understanding of Lubrication Mechanisms in Total Knee Replacements – Part II: Numerical Modeling.” Tribology International, 106809. doi:10.1016/j.triboint.2020.106809.

Habchi, W. , I. Demirci , D. Eyheramendy , G. Morales-Espejel , and P. Vergne . 2007. “A Finite Element Approach of Thin Film Lubrication in Circular EHD Contacts.” Tribology International 40 (10–12): 1466–1473. doi:10.1016/j.triboint.2007.01.017.

Habchi, W. 2018. Finite Element Modeling of Elastohydrodynamic Lubrication Problems. Newark: John Wiley & Sons Incorporated. https://ebookcentral.proquest.com/lib/gbv/detail.action?docID=5322515.

Parkes, Maria , Connor Myant , Philippa M. Cann , and Janet S.S. Wong . 2014. “The Effect of Buffer Solution Choice on Protein Adsorption and Lubrication”. Tribology International 72: 108–117. doi:10.1016/j.triboint.2013.12.005.

Parkes, Maria , Connor Myant , Philippa M. Cann , and Janet S.S. Wong . 2015. “Synovial Fluid Lubrication: The Effect of Protein Interactions on Adsorbed and Lubricating Films”. Biotribology 1–2: 51–60. doi:10.1016/j.biotri.2015.05.001.

Nečas, D. , Y. Sawae , T. Fujisawa , K. Nakashima , T. Morita , T. Yamaguchi , M. Vrbka , I. Křupka , and M. Hartl . 2017. “The Influence of Proteins and Speed on Friction and Adsorption of Metal/Uhmwpe Contact Pair”. Biotribology 11: 51–59. doi:10.1016/j.biotri.2017.03.003.

Choudhury, D. , F. Urban , M. Vrbka , M. Hartl , and I. Krupka . 2015. “A Novel Tribological Study on Dlc-Coated Micro-Dimpled Orthopedics Implant Interface”. Journal of the Mechanical Behavior of Biomedical Materials 45: 121–131. doi:10.1016/j.jmbbm.2014.11.028.

Dong, Y. , P. Svoboda , M. Vrbka , D. Kostal , F. Urban , J. Cizek , P. Roupcova , H. Dong , I. Krupka , and M. Hartl . 2016. “Towards Near-Permanent Cocrmo Prosthesis Surface by Combining Micro-Texturing and Low Temperature Plasma Carburising”. Journal of the Mechanical Behavior of Biomedical Materials 55: 215–227. doi:10.1016/j.jmbbm.2015.10.023.

Nečas, D. , H. Usami , T. Niimi , Y. Sawae , I. Křupka , and M. Hartl . 2020. “Running-In Friction of Hip Joint Replacements Can Be Significantly Reduced: The Effect of Surface-Textured Acetabular Cup”. Friction 8: 1137–1152. doi:10.1007/s40544-019-0351-x.

Computational Modeling of Biotribology on Artificial Knee Joints

Jones GB . Arthroplasty of the knee by the Walldius prosthesis. J Bone Joint Surg Br. 1968;50: 505–510. Available: http://www.ncbi.nlm.nih.gov/pubmed/5726903.

Maradit Kremers H , Larson DR , Crowson CS , Kremers WK , Washington RE , Steiner CA , et al. Prevalence of Total Hip and Knee Replacement in the United States. J Bone Joint Surg Am. 2015;97: 1386–1397. doi:10.2106/JBJS.N.01141.

Berry DJ , Harmsen WS , Cabanela ME , Morrey BF . Twenty-five-year survivorship of two thousand consecutive primary Charnley total hip replacements: factors affecting survivorship of acetabular and femoral components. J Bone Joint Surg Am. 2002;84-A: 171–177. Available: http://www.ncbi.nlm.nih.gov/pubmed/11861721.

Bae DK , Song SJ , Park MJ , Eoh JH , Song JH , Park CH . Twenty-Year Survival Analysis in Total Knee Arthroplasty by a Single Surgeon. J Arthroplasty. 2012;27: 1297–1304.e1. doi:10.1016/j.arth.2011.10.027.

Bourne RB , Chesworth BM , Davis AM , Mahomed NN , Charron KDJ . Patient satisfaction after total knee arthroplasty: Who is satisfied and who is not? Clin Orthop Relat Res. 2010;468: 57–63. doi:10.1007/s11999-009-1119-9.

Pabinger C , Berghold A , Boehler N , Labek G. Revision rates after knee replacement: Cumulative results from worldwide clinical studies versus joint registers. Osteoarthr Cartil. 2013;21: 263–268. doi:10.1016/j.joca.2012.11.014.

Von Keudell A , Sodha S , Collins J , Minas T , Fitz W , Gomoll AH . Patient satisfaction after primary total and unicompartmental knee arthroplasty: An age-dependent analysis. Knee. 2014;21: 180–184. doi:10.1016/j.knee.2013.08.004.

National joint registry 15th annual report 2018. Natl Jt Regist England, Wales, North Irel Isle Man. 2018. doi:10.1038/nmat2505.

Ranawat AS , Mohanty SS , Goldsmith SE , Rasquinha VJ , Rodriguez JA , Ranawat CS . Experience with an all-polyethylene total knee arthroplasty in younger, active patients with follow-up from 2 to 11 years. J Arthroplasty. 2005;20: 7–11. doi:10.1016/j.arth.2005.04.027.

Kretzer JP , Reinders J , Sonntag R , Hagmann S , Streit M , Jeager S , et al. Wear in total knee arthroplasty – Just a question of polyethylene?: Metal ion release in total knee arthroplasty. Int Orthop. 2014;38: 335–340. doi:10.1007/s00264-013-2162-4.

O’Brien ST , Luo Y , Brandt JM . In-vitro and in-silico investigations on the influence of contact pressure on cross-linked polyethylene wear in total knee replacements. Wear. 2015;332–333: 687–693. doi:10.1016/j.wear.2015.02.048.

Miura H , Higaki H , Nakanishi Y , Mawatari T , Moro-Oka T , Murakami T , et al. Prediction of total knee arthroplasty polyethylene wear using the wear index. J Arthroplasty. 2002;17: 760–766. doi:10.1054/arth.2002.33546.

Shu L , Li S , Sugita N. Systematic review of computational modelling for biomechanics analysis of total knee replacement. Biosurf Biotribol. 2020;6: 3–11. doi:10.1049/bsbt.2019.0012.

Knight LA , Pal S , Coleman JC , Bronson F , Haider H , Levine DL , et al. Comparison of long-term numerical and experimental total knee replacement wear during simulated gait loading. J Biomech. 2007;40: 1550–1558. doi:10.1016/j.jbiomech.2006.07.027.

Willing R , Kim IY . Three dimensional shape optimization of total knee replacements for reduced wear. Struct Multidiscip Optim. 2009;38: 405–414. doi:10.1007/s00158-008-0281-0.
Kang K-T , Koh Y-G , Jung M , Nam J-H , Son J , Lee YH , et al. The effects of posterior cruciate ligament deficiency on posterolateral corner structures under gait- and squat-loading conditions. Bone Jt Res. 2017;6: 31–42. doi:10.1302/2046-3758.61.BJR-2016-0184.R1.
Carr BC , Goswami T. Knee implants – Review of models and biomechanics. Mater Des. 2009;30: 398–413. doi:10.1016/j.matdes.2008.03.032.
Nečas D , Vrbka M , Marian M , Rothammer B , Tremmel S , Wartzack S , et al. Towards the understanding of lubrication mechanisms in total knee replacements – Part I: Experimental investigations. Tribol Int. 2021;156: 106874. doi:10.1016/j.triboint.2021.106874.
Marian M , Orgeldinger C , Rothammer B , Nečas D , Vrbka M , Křupka I , et al. Towards the understanding of lubrication mechanisms in total knee replacements – Part II: Numerical modeling. Tribol Int. 2021;156. doi:10.1016/j.triboint.2020.106809.
Archard JF , Hirst W. The wear of metals under unlubricated conditions. Proc R Soc A Math Phys Eng Sci. 1956;236: 397–410. doi:10.1098/rspa.1956.0144.
Innocenti B , Labey L , Kamali A , Pascale W , Pianigiani S. Development and Validation of a Wear Model to Predict Polyethylene Wear in a Total Knee Arthroplasty: A Finite Element Analysis. Lubricants. 2014;2: 193–205. doi:10.3390/lubricants2040193.
Wang A. A unified theory of wear for ultra-high molecular weight polyethylene in multi-directional sliding. Wear. 2001;248: 38–47. doi:10.1016/S0043-1648(00)00522-6.
Kang L , Galvin AL , Brown TD , Jin Z , Fisher J. Quantification of the effect of cross-shear on the wear of conventional and highly cross-linked UHMWPE. J Biomech. 2008;41: 340–346. doi:10.1016/j.jbiomech.2007.09.005.
Abdelgaied A , Brockett CL , Liu F , Jennings LM , Jin Z , Fisher J. The effect of insert conformity and material on total knee replacement wear. Proc Inst Mech Eng Part H J Eng Med. 2014;228: 98–106. doi:10.1177/0954411913513251.
Abdelgaied A , Fisher J , Jennings LM . A comprehensive combined experimental and computational framework for pre-clinical wear simulation of total knee replacements. J Mech Behav Biomed Mater. 2018;78: 282–291. doi:10.1016/j.jmbbm.2017.11.022.
Benjamin J , Szivek J , Dersam G , Persselin S , Johnson R. Linear and volumetric wear of tibial inserts in posterior cruciate-retaining knee arthroplasties. Clin Orthop Relat Res. 2001; 131–138. doi:10.1097/00003086-200111000-00016.
Hoshino A , Fukuoka Y , Ishida A. Accurate in vivo measurement of polyethylene wear in total knee arthroplasty. J Arthroplasty. 2002;17: 490–496. doi:10.1054/arth.2002.32172.
Price AJ , Short A , Kellett C , Beard D , Gill H , Pandit H , et al. Ten-year in vivo wear measurement of a fully congruent mobile bearing unicompartmental knee arthroplasty. J Bone Jt Surg – Ser B. 2005;87: 1493–1497. doi:10.1302/0301-620X.87B11.16325.
Gill HS , Waite JC , Short A , Kellett CF , Price AJ , Murray DW . In vivo measurement of volumetric wear of a total knee replacement. Knee. 2006;13: 312–317. doi:10.1016/j.knee.2006.04.001.
Kop AM , Swarts E. Quantification of polyethylene degradation in mobile bearing knees: A retrieval analysis of the Anterior-Posterior-Glide (APG) and Rotating Platform (RP) Low Contact Stress (LCS) knee. Acta Orthop. 2007;78: 364–370. doi:10.1080/17453670710013942.
Wang XH , Li H , Dong X , Zhao F , Cheng CK . Comparison of ISO 14243-1 to ASTM F3141 in terms of wearing of knee prostheses. Clin Biomech. 2019;63: 34–40. doi:10.1016/j.clinbiomech.2019.02.008.
Shu L , Hashimoto S , Sugita N. Enhanced In-Silico Polyethylene Wear Simulation of Total Knee Replacements During Daily Activities. Ann Biomed Eng. 2021;49: 322–333. doi:10.1007/s10439-020-02555-4.
O'Brien S , Luo Y , Wu C , Petrak M , Bohm E , Brandt JM . Computational development of a polyethylene wear model for the articular and backside surfaces in modular total knee replacements. Tribol Int. 2013;59: 284–291. doi:10.1016/j.triboint.2012.03.020.
Gao L , Hua Z , Hewson R , Andersen MS , Jin Z. Elastohydrodynamic lubrication and wear modelling of the knee joint replacements with surface topography. Biosurf Biotribol. 2018;4: 18–23. doi:10.1049/bsbt.2017.0003.
Sharif KJ , Evans HP , Snidle RW , Barnett D , Egorov IM . Effect of elastohydrodynamic film thickness on a wear model for worm gears. Proc Inst Mech Eng Part J J Eng Tribol. 2006;220: 295–306. doi:10.1243/13506501JET122.

Gao L , Wang F , Yang P , Jin Z. Effect of 3D physiological loading and motion on elastohydrodynamic lubrication of metal-on-metal total hip replacements. Med Eng Phys. 2009;31: 720–729. doi:10.1016/j.medengphy.2009.02.002.

Parkes M , Myant C , Cann PM , Wong JSS . The effect of buffer solution choice on protein adsorption and lubrication. Tribol Int. 2014;72: 108–117. doi:10.1016/j.triboint.2013.12.005.

Wang FC , Jin ZM . Prediction of elastic deformation of acetabular cups and femoral heads for lubrication analysis of artificial hip joints. Proc Inst Mech Eng Part J Eng Tribol. 2004;218: 201–208. doi:10.1243/1350650041323331.

Venner CH . Multigrid techniques: A fast and efficient method for the numerical simulation of elastohydrodynamically lubricated point contact problems. Proc Inst Mech Eng Part J Eng Tribol. 2000;214: 43–61. doi:10.1243/1350650001543007.

Morlock M , Schneider E , Bluhm A , Vollmer M , Bergmann G , Müller V , et al. Duration and frequency of every day activities in total hip patients. J Biomech. 2001;34: 873–881. Available: http://www.ncbi.nlm.nih.gov/pubmed/11410171.

Shu L , Yamamoto K , Kai S , Inagaki J , Sugita N. Symmetrical cruciate-retaining versus medial pivot prostheses: The effect of intercondylar sagittal conformity on knee kinematics and contact mechanics. Comput Biol Med. 2019;108: 101–110. doi:10.1016/j.compbiomed.2019.03.005.

Battaglia S , Belvedere C , Jaber SA , Affatato S , D'Angeli V , Leardini A. A new protocol from real joint motion data for wear simulation in total knee arthroplasty: Stair climbing. Med Eng Phys. 2014;36: 1605–1610. doi:10.1016/j.medengphy.2014.08.010.

Schwiesau J , Schilling C , Kaddick C , Utzschneider S , Jansson V , Fritz B , et al. Definition and evaluation of testing scenarios for knee wear simulation under conditions of highly demanding daily activities. Med Eng Phys. 2013;35: 591–600. doi:10.1016/j.medengphy.2012.07.003.

Reinders J , Sonntag R , Vot L , Gibney C , Nowack M , Kretzer JP . Wear testing of moderate activities of daily living using in vivo measured knee joint loading. PLoS One. 2015;10: 9–11. doi:10.1371/journal.pone.0123155.

Twiggs JG , Wakelin EA , Roe JP , Dickison DM , Fritsch BA , Miles BP , et al. Patient-Specific Simulated Dynamics After Total Knee Arthroplasty Correlate With Patient-Reported Outcomes. J Arthroplasty. 2018;33: 2843–2850. doi:10.1016/j.arth.2018.04.035.

Fregly BJ , Sawyer WG , Harman MK , Banks SA . Computational wear prediction of a total knee replacement from in vivo kinematics. J Biomech. 2005;38: 305–314. doi:10.1016/j.jbiomech.2004.02.013.

Chen Z , Zhang X , Ardestani MM , Wang L , Liu Y , Lian Q , et al. Prediction of in vivo joint mechanics of an artificial knee implant using rigid multi-body dynamics with elastic contacts. Proc Inst Mech Eng Part H J Eng Med. 2014;228: 564–575. doi:10.1177/0954411914537476.

Zhang J , Chen Z , Wang L , Li D , Jin Z. A patient-specific wear prediction framework for an artificial knee joint with coupled musculoskeletal multibody-dynamics and finite element analysis. Tribol Int. 2017;109: 382–389. doi:10.1016/j.triboint.2016.10.050.

Koh YG , Son J , Kwon OR , Kwon SK , Kang KT . Tibiofemoral conformity variation offers changed kinematics and wear performance of customized posterior-stabilized total knee arthroplasty. Knee Surgery, Sport Traumatol Arthrosc. 2019;27: 1213–1223. doi:10.1007/s00167-018-5045-9.

Koh YG , Park KM , Lee HY , Park JH , Kang KT . Prediction of wear performance in femoral and tibial conformity in patient-specific cruciate-retaining total knee arthroplasty. J Orthop Surg Res. 2020;15: 1–10. doi:10.1186/s13018-020-1548-4.

Koh Y-G , Jung K-H , Hong H-T , Kim K-M , Kang K-T. Optimal Design of Patient-Specific Total Knee Arthroplasty for Improvement in Wear Performance. J Clin Med. 2019;8: 2023. doi:10.3390/jcm8112023.

Koh YG , Park KM , Lee HY , Kang KT . Influence of tibiofemoral congruency design on the wear of patient-specific unicompartmental knee arthroplasty using finite element analysis. Bone Jt Res. 2019;8: 156–164. doi:10.1302/2046-3758.83.BJR-2018-0193.R1.

Shu L , Yamamoto K , Yao J , Saraswat P , Liu Y , Mitsuishi M , et al. A subject-specific finite element musculoskeletal framework for mechanics analysis of a total knee replacement. J Biomech. 2018;77: 146–154. doi:10.1016/j.jbiomech.2018.07.008.

McColl IR , Ding J , Leen SB . Finite element simulation and experimental validation of fretting wear. Wear. 2004;256: 1114–1127. doi:10.1016/j.wear.2003.07.001.

Development of a Multibody Biomechanical Model of the Human Upper Limb

A. Ruggiero e A. Sicilia , “A mixed elasto-hydrodynamic lubrication model for wear calculation in artificial hip joints,” Lubricants, vol. 8, n. 7, p. 72, 2020.

A. Ruggiero e A. Sicilia , “Lubrication modeling and wear calculation in artificial hip joint during the gait,” Tribology International, vol. 142, p. 105993, 2020.

A. Ruggiero , A. Sicilia e S. Affatato , “In silico total hip replacement wear testing in the framework of ISO 14242-3 accounting for mixed elasto-hydrodynamic lubrication effects,” Wear, p. 203420, 2020.

J. Hu , Z. Chen , H. Xin , Q. Zhang e Z. Jin , “Musculoskeletal multibody dynamics simulation of the contact mechanics and kinematics of a natural knee joint during a walking cycle,” Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, vol. 232, n. 5, pp. 508–519, 2018.

P. A. Varady , U. Glitsch e P. Augat , “Loads in the hip joint during physically demanding occupational tasks: A motion analysis study,” Journal of Biomechanics, vol. 48, n. 12, pp. 3227–3233, 2015.

A. Ruggiero , R. D’Amato e N. Ungureanu , “Musculoskeletal multibody simulations for the optimal tribological design of human prostheses: the case of the ankle joint,” Materials Science and Engineering, vol. 749, n. 1, p. 012008, 2020.

A. P. Stylianou , T. M. Guess e M. Kia , “Multibody muscle driven model of an instrumented prosthetic knee during squat and toe rise motions,” Journal of Biomechanical Engineering, vol. 135, n. 4, 2013.

A. Ruggiero , M. Merola e S. Affatato , “On the biotribology of total knee replacement: A new roughness measurements protocol on in vivo condyles considering the dynamic loading from musculoskeletal multibody model,” Measurement, vol. 112, pp. 22–28, 2017.

S. Affatato , M. Merola e A. Ruggiero , “Development of a novel in silico model to investigate the influence of radial clearance on the acetabular cup contact pressure in hip implants,” Materials, vol. 11, n. 8, p. 1282, 2018.

A. Ruggiero , M. Merola e S. Affatato , “Finite element simulations of hard-on-soft hip joint prosthesis accounting for dynamic loads calculated from a musculoskeletal model during walking,” Materials, vol. 11, n. 4, p. 574, 2018.

G. Bergmann , A. Bender , J. Dymke , G. Duda e P. Damm , “Standardized loads acting in hip implants,” PloS one, vol. 11, n. 5, p. e0155612, 2016.

J.-P. Kassi , M. O. Heller , U. Stoeckle , C. Perka e G. N. Duda , “Stair climbing is more critical than walking in pre-clinical assessment of primary stability in cementless THA in vitro,” Journal of Biomechanics, vol. 38, n. 5, pp. 1143–1154, 2005.

P. Westerhoff , F. Graichen , A. Bender , A. Halder , A. Beier , A. Rohlmann e G. Bergmann , “In vivo measurement of shoulder joint loads during activities of daily living,” Journal of Biomechanics, vol. 42, n. 12, pp. 1840–1849, 2009.

M. Nordin e V. H. Frankel , Basic biomechanics of the musculoskeletal system, Lippincott Williams & Wilkins, Philadelphia, PA, 2001.

U. Trinler e R. Baker , “Estimated landmark calibration of biomechanical models for inverse kinematics,” Medical Engineering & Physics, vol. 51, pp. 79–83, 2018.

M. T. Silva , A. F. Pereira e J. M. Martins , “An efficient muscle fatigue model for forward and inverse dynamic analysis of human movements,” Procedia IUTAM, vol. 2, pp. 262–274, 2011.

M. P. Silva e J. A. Ambrosio , “Solution of redundant muscle forces in human locomotion with multibody dynamics and optimization tools,” *Mechanics Based Design of Structures and Machines* : An International Journal, vol. 31, n. 3, pp. 381–411, 2003.

N. Curtis , “Craniofacial biomechanics: an overview of recent multibody modelling studies,” Journal of Anatomy, vol. 218, n. 1, pp. 16–25, 2011.

S. Duprey , A. Naaim , F. Moissenet , M. Begon e L. Cheze , “Kinematic models of the upper limb joints for multibody kinematics optimisation: An overview,” Journal of Biomechanics, vol. 62, pp. 87–94, 2017.

K. Huynh , I. Gibson , B. Jagdish e W. Lu , “Development and validation of a discretised multi-body spine model in LifeMOD for biodynamic behaviour simulation,” Computer Methods in Biomechanics and Biomedical Engineering, vol. 18, n. 2, pp. 175–184, 2015.

A. Ruggiero , e A. Sicilia . A novel explicit analytical multibody approach for the analysis of upper limb dynamics and joint reactions calculation considering muscle wrapping. Applied

Sciences, vol. 10, n. 21, p. 7760, 2020.
A. Shabana , Dynamics of multibody systems, Cambridge University Press, 2020.
P. E. Nikravesh e G. Gim , “Systematic construction of the equations of motion for multibody systems containing closed kinematic loops,” Journal of Mechanical Design, vol. 115, n. 1, pp. 143–149, 1993.
H. Oliveira , “Inverse Dynamic Analysis of the Human Locomotion Apparatus for Gait,” Instituto Superior Técnico, Lisbon, 2016.
K. Jovanovic , J. Vranic e N. Miljkovic , “Hill’s and Huxley’s muscle models: Tools for simulations in biomechanics,” Serbian Journal of Electrical Engineering, vol. 12, n. 1, pp. 53–67, 2015.
M. Millard , T. Uchida , A. Seth e S. L. Delp , “Flexing computational muscle: modeling and simulation of musculotendon dynamics,” Journal of Biomechanical Engineering, vol. 135, n. 2, 2013.
F. Romero e F. Alonso , “A comparison among different Hill-type contraction dynamics formulations for muscle force estimation,” Mechanical Sciences, vol. 7, n. 1, p. 19, 2016.
C. John , “Complete Description of the Thelen 2003 Muscle Model,” OpenSim Documentation, 2011. https://simtk-confluence.stanford.edu/display/OpenSim/Thelen+2003+Muscle+Model.
D. G. Thelen , “Adjustment of muscle mechanics model parameters to simulate dynamic contractions in older adults,” Journal of Biomechanical Engineering, vol. 125, n. 1, pp. 70–77, 2003.
M. Hada , D. Yamada e T. Tsuji , “An analysis of equivalent impedance characteristics by modeling the human musculoskeletal structure as a multibody system,” Proceedings of the ECCOMAS Thematic Conference, pp. 1–20, 2007.
F. Gao , M. Damsgaard , J. Rasmussen e S. T. Christensen , “Computational method for muscle-path representation in musculoskeletal models,” Biological Cybernetics, vol. 87, n. 3, pp. 199–210, 2002.
O. Zarifi e I. Stavness , “Muscle wrapping on arbitrary meshes with the heat method,” Computer Methods in Biomechanics and Biomedical Engineering, vol. 20, n. 2, pp. 119–129, 2017.
I. Stavness , M. Sherman e S. Delp , “A general approach to muscle wrapping over multiple surfaces,” 2012.
A. Scholz , I. Stavness , M. Sherman , S. Delp e A. Kecskemethy , “Improved muscle wrapping algorithms using explicit path-error Jacobians,” Computational Kinematics, pp. 395–403, 2014.
D. G. Thelen , F. C. Anderson e S. L. Delp , “Generating dynamic simulations of movement using computed muscle control,” Journal of Biomechanics, vol. 36, n. 3, pp. 321–328, 2003.

Metal-Organic Frameworks-Polymer Composites for Practical Applications

Hutchings I , Shipway P. Trybology: Friction and Wear of Engineering Materials. 2nd edition. Elsevier Ltd; 2017.
Rehman M , Madni A , Webster TJ . The era of biofunctional biomaterials in orthopedics: what does the future hold? Expert Rev Med Dev. [Internet]. 2018;15(3):193–204. Available from: http://dx.doi.org/10.1080/17434440.2018.1430569.
Zivić F , Babić M , Grujović N , Mitrović S. Tribometry of materials for bioengineering applications. Tribol Ind. 2010;32(1):25–32.
Buxadera-Palomero J , Calvo C , Torrent-Camarero S , Gil FJ , Mas-Moruno C , Canal C , et al. Biofunctional polyethylene glycol coatings on titanium: an in vitro-based comparison of functionalization methods. Colloids Surfaces B Biointerfaces [Internet]. 2017;152:367–375. Available from: http://dx.doi.org/10.1016/j.colsurfb.2017.01.042.
Uwais ZA , Hussein MA , Samad MA , Al-Aqeeli N. Surface modification of metallic biomaterials for better tribological properties: a review. Arab J Sci Eng. 2017;42(11):4493–4512.
Nath S , Sinha N , Basu B. Microstructure, mechanical and tribological properties of microwave sintered calcia-doped zirconia for biomedical applications. Ceram Int. 2008;34(6):1509–1520.
Avilés MD , Sánchez C , Pamies R , Sanes J , Bermúdez MD . Ionic liquid crystals in tribology. Lubricants. 2019;7(9):72.

Madhavasarma P , Veeraragavan P , Kumaravel S , Sridevi M. Studies on physiochemical modifications on biologically important hydroxyapatite materials and their characterization for medical applications. Biophys Chem [Internet]. 2020;267(September):106474. Available from: https://doi.org/10.1016/j.bpc.2020.106474.

Mishra A , Khobragade N , Sikdar K , Chakraborty S , Kumar SB , Roy D. Study of mechanical and tribological properties of Nanomica dispersed hydroxyapatite based composites for biomedical applications. Adv Mater Sci Eng. 2017;2017.

Chawla K , Lee S , Lee BP , Dalsin JL , Messersmith PB , Spencer ND . A novel low-friction surface for biomedical applications: modification of poly(dimethylsiloxane) (PDMS) with polyethylene glycol(PEG)-DOPA-lysine. J Biomed Mater Res A. 2009;90(3):742–749.

Andresen Eguiluz RC , Cook SG , Brown CN , Wu F , Pacifici NJ , Bonassar LJ , et al. Fibronectin mediates enhanced wear protection of lubricin during shear. Biomacromolecules. 2015;16(9):2884–2894.

Sahoo P , Das SK , Paulo Davim J. Tribology of materials for biomedical applications [Internet]. Mechanical Behaviour of Biomaterials. Elsevier Ltd.; 2019. 1–45. Available from: https://doi.org/10.1016/B978-0-08-102174-3.00001-2.

Zhou ZR , Jin ZM . Biotribology: recent progresses and future perspectives. Biosurface and Biotribology. 2015;1(1):3–24.

Zivic F. Nanotribometer area of application. Tribol Ind. 2007;29(3–4):29–34.

Choubey A , Basu B , Balasubramaniam R. Tribological behaviour of Ti-based alloys in simulated body fluid solution at fretting contacts. Mater Sci Eng A. 2004;379(1–2):234–239.

Taylor BL , Mills TB . Using a three-ball-on-plate configuration for soft tribology applications. J Food Eng. 2020;274(April):109838.

Myant C , Spikes HA , Stokes JR . Influence of load and elastic properties on the rolling and sliding friction of lubricated compliant contacts. Tribol Int [Internet]. 2010;43(1–2):55–63. Available from: http://dx.doi.org/10.1016/j.triboint.2009.04.034.

Bowland P , Ingham E , Jennings L , Fisher J. Review of the biomechanics and biotribology of osteochondral grafts used for surgical interventions in the knee. Proc Inst Mech Eng Part H J Eng Med. 2015;229(12):879–888.

Winkeljann B , Bussmann AB , Bauer MG , Lieleg O. Oscillatory tribology performed with a commercial shear rheometer. Biotribology. 2018;14(May):11–18.

Rigaud E , Perret-Liaudet JL , Belin M , Joly-Pottuz L , Martin JM . An original dynamic tribotest to discriminate friction and viscous damping. Tribol Int. 2010;43(1–2):320–329.

Carvalho AL , Vilhena LM , Ramalho A. Study of the frictional behavior of soft contact lenses by an innovative method. Tribol Int. 2021;153(September):3–9.

Tyurin A , Ganus G , Stepanov M , Ismailov G. Measurement instruments and software used in biotribology research laboratory. Electr Control Commun Eng. 2015;8(1):30–36.

Li X , Lu L , Li J , Zhang X , Gao H. Mechanical properties and deformation mechanisms of gradient nanostructured metals and alloys. Nat Rev Mater [Internet]. 2020;5(9):706–723. Available from: http://dx.doi.org/10.1038/s41578-020-0212-2.

Camara CG , Escobar J V ., Hird JR , Putterman SJ . Correlation between nanosecond X-ray flashes and stick-slip friction in peeling tape. Nature. 2008;455(7216):1089–1092.

Gay C , Leibler L , Gay C , Leibler L , Letters R , Physical A. Theory of tackiness. Phys Rev Lett. 2016;82(5):936–939.

Dou X , Koltonow AR , He X , Jang HD , Wang Q , Chung YW , et al. Self-dispersed crumpled graphene balls in oil for friction and wear reduction. Proc Natl Acad Sci U S A. 2016;113(6):1528–1533.

Su G , Yang S , Jiang Y , Li J , Li S , Ren JC , et al. Modeling chemical reactions on surfaces: The roles of chemical bonding and van der Waals interactions. Prog Surf Sci [Internet]. 2019;94(4):100561. Available from: https://doi.org/10.1016/j.progsurf.2019.100561.

Yuan D , Zhang Y , Ho W , Wu R. Effects of van der Waals dispersion interactions in density functional studies of adsorption, catalysis, and tribology on metals. J Phys Chem C. 2020;124(31):16926–16942.

Schmidt TA , Gastelum NS , Nguyen QT , Schumacher BL , Sah RL . Boundary lubrication of articular cartilage: role of synovial fluid constituents. Arthritis Rheum. 2007;56(3):882–891.

Tamer TM . Hyaluronan and synovial joint: function, distribution and healing. Interdiscip Toxicol. 2013;6(3):111–125.

Flannery CR , Hughes CE , Schumacher BL , Tudor D , Aydelotte MB , Kuettner KE , et al. Articular cartilage superficial zone protein (SZP) is homologous to megakaryocyte stimulating factor precursor and is a multifunctional proteoglycan with potential growth-promoting, cytoprotective, and lubricating properties in cartilage metabolism. Biochem Biophys Res Commun. 1999;254(3):535–541.
Graham HK , Holmes DF , Watson RB , Kadler KE . Identification of collagen fibril fusion during vertebrate tendon morphogenesis. The process relies on unipolar fibrils and is regulated by collagen-proteoglycan interaction. J Mol Biol. 2000;295(4):891–902.
Flowers SA , Zieba A , Örnros J , Jin C , Rolfson O , Björkman LI , et al. Lubricin binds cartilage proteins, cartilage oligomeric matrix protein, fibronectin and collagen II at the cartilage surface. Sci Rep. 2017;7(1):1–11.
Kadler KE , Hill A , Canty-Laird EG . Collagen fibrillogenesis: fibronectin, integrins, and minor collagens as organizers and nucleators. Curr Opin Cell Biol. 2008;20(5):495–501.
Link JM , Salinas EY , Hu JC , Athanasiou KA . The tribology of cartilage: mechanisms, experimental techniques, and relevance to translational tissue engineering. Clin Biomech [Internet]. 2020;79(October):104880. Available from: https://doi.org/10.1016/j.clinbiomech.2019.10.016.
Villegas M , Zhang Y , Abu Jarad N , Soleymani L , Didar TF . Liquid-infused surfaces: a review of theory, design, and applications. ACS Nano. 2019;13(8):8517–8536.
Furukawa H , Cordova KE , O'Keeffe M , Yaghi OM . The chemistry and applications of metal-organic frameworks. Science. 2013;341(6149).
Chen J , Zhu Y , Kaskel S. Porphyrin-based metal–organic frameworks for biomedical applications. Angew Chemie – Int Ed. 2021;60(10):5010–5035.
Diercks CS , Yaghi OM . The atom, the molecule, and the covalent organic framework. Science. 2017;355(6328).
Haase F , Hirschle P , Freund R , Furukawa S , Ji Z , Wuttke S. Beyond frameworks: structuring reticular materials across nano-, meso-, and bulk regimes. Angew Chemie – Int Ed. 2020;59(50):22350–22370.
Lee JSM , Cooper AI . Advances in conjugated microporous polymers. Chem Rev. 2020;120(4):2171–2214.
Liu D , Zou D , Zhu H , Zhang J. Mesoporous metal–organic frameworks: synthetic strategies and emerging applications. Small. 2018;14(37):1–40.
Gropp C , Ma T , Hanikel N , Yaghi OM . Design of higher valency in covalent organic frameworks. Science. 2020;370(6515).
Wang B , Côté AP , Furukawa H , O'Keeffe M , Yaghi OM . Colossal cages in zeolitic imidazolate frameworks as selective carbon dioxide reservoirs. Nature. 2008;453(7192):207–211.
Lee HP , Gaharwar AK . Light-responsive inorganic biomaterials for biomedical applications. Adv Sci. 2020;7(17):2000863.
Begum S , Hassan Z , Bräse S , Tsotsalas M. Polymerization in MOF-confined nanospaces: tailored architectures, functions, and applications. Langmuir. 2020;36(36):10657–10673.
Zhu W , Zhao J , Chen Q , Liu Z. Nanoscale metal-organ frameworks and coordination polymers as theranostic platforms for cancer treatment. Coord Chem Rev [Internet]. 2019;398:113009. Available from: https://doi.org/10.1016/j.ccr.2019.07.006
He C , Liu D , Lin W. Nanomedicine applications of hybrid nanomaterials built from metal-ligand coordination bonds: nanoscale metal-organic frameworks and nanoscale coordination polymers. Chem Rev. 2015;115(19):11079–11108.
Vialar P , Merzeau P , Giasson S , Drummond C. Compliant surfaces under shear: elastohydrodynamic lift force. Langmuir. 2019;35(48):15605–15613.
Di Puccio F , Mattei L. Biotribology of artificial hip joints. World J Orthop. 2015;6(1):77–94.
Cobb JA , Dunn AC , Kwon J , Sarntinoranont M , Sawyer WG , Tran-Son-Tay R. A novel method for low load friction testing on living cells. Biotechnol Lett. 2008;30(5):801–806.
Dean D , Hemmer J , Vertegel A , LaBerge M. Frictional behavior of individual vascular smooth muscle cells assessed by lateral force microscopy. Materials (Basel). 2010;3(9):4668–4680.
Warren KM , Islam MM , Leduc PR , Steward R. 2D and 3D Mechanobiology in human and nonhuman systems. ACS Appl Mater Interfaces. 2016;8(34):21869–21882.
Meng HM , Hu XX , Kong GZ , Yang C , Fu T , Li ZH , et al. Aptamer-functionalized nanoscale metal-organic frameworks for targeted photodynamic therapy. Theranostics.

2018;8(16):4332–4344.
Ma K , Idrees KB , Son FA , Maldonado R , Wasson MC , Zhang X , et al. Fiber composites of metal-organic frameworks. Chem Mater. 2020;32(17):7120–7140.
Zhang ZH , Duan FH , Tian JY , He JY , Yang LY , Zhao H , et al. Aptamer-embedded zirconium-based metal-organic framework composites prepared by de novo bio-inspired approach with enhanced biosensing for detecting trace analytes. ACS Sensors. 2017;2(7):982–989.
Zhang GY , Deng SY , Cai WR , Cosnier S , Zhang XJ , Shan D. Magnetic zirconium hexacyanoferrate (II) nanoparticle as tracing tag for electrochemical DNA Assay. Anal Chem. 2015;87(17):9093–9100.
Della Giustina G , Zambon A , Lamberti F , Elvassore N , Brusatin G. Straightforward micropatterning of oligonucleotides in microfluidics by novel spin-on ZrO2 surfaces. ACS Appl Mater Interfaces. 2015;7(24):13280–13288.
Gholizadeh E , Belibel R , Bachelart T , Bounadji C , Barbaud C. Chemical grafting of cholesterol on monomer and PDMMLA polymers, a step towards the development of new polymers for biomedical applications. RSC Adv. 2020;10(54):32602–32608.
Belibel R , Sali S , Marinval N , Garcia-Sanchez A , Barbaud C , Hlawaty H. PDMMLA derivatives as a promising cardiovascular metallic stent coating: physicochemical and biological evaluation. Mater Sci Eng C [Internet]. 2020;117(June):111284. Available from: https://doi.org/10.1016/j.msec.2020.111284
Ryu UJ , Jee S , Rao PC , Shin J , Ko C , Yoon M , et al. Recent advances in process engineering and upcoming applications of metal–organic frameworks. Coord Chem Rev [Internet]. 2021;426:213544. Available from: https://doi.org/10.1016/j.ccr.2020.213544
Zhao N , Cai K , He H. The synthesis of metal-organic frameworks with template strategies. Dalt Trans. 2020;49(33):11467–11479.
Krishtab M , Stassen I , Stassin T , Cruz AJ , Okudur OO , Armini S , et al. Vapor-deposited zeolitic imidazolate frameworks as gap-filling ultra-low-k dielectrics. Nat Commun. 2019;10(1):1–9.
Abbasian M , Massoumi B , Mohammad-Rezaei R , Samadian H , Jaymand M. Scaffolding polymeric biomaterials: are naturally occurring biological macromolecules more appropriate for tissue engineering? Int J Biol Macromol [Internet]. 2019;134:673–694. Available from: https://doi.org/10.1016/j.ijbiomac.2019.04.197
Hedayati M , Neufeld MJ , Reynolds MM , Kipper MJ . The quest for blood-compatible materials: recent advances and future technologies. Mater Sci Eng R Reports [Internet]. 2019;138(March):118–152. Available from: https://doi.org/10.1016/j.mser.2019.06.002
Howarth AJ , Liu Y , Li P , Li Z , Wang TC , Hupp JT , et al. Chemical, thermal and mechanical stabilities of metal-organic frameworks. Nat Rev Mater. 2016;1(15018):1–15.
Wu H , Yildirim T , Zhou W. Exceptional mechanical stability of highly porous zirconium metal-organic framework UiO-66 and its important implications. J Phys Chem Lett. 2013;4(6):925–930.
Usman KAS , Maina JW , Seyedin S , Conato MT , Payawan LM , Dumée LF , et al. Downsizing metal–organic frameworks by bottom-up and top-down methods. NPG Asia Mater. 2020;12(1).
Simon-Yarza T , Mielcarek A , Couvreur P , Serre C. Nanoparticles of metal-organic frameworks: on the road to in vivo efficacy in biomedicine. Adv Mater. 2018;30(37):1–15.
Dang S , Zhu QL , Xu Q. Nanomaterials derived from metal-organic frameworks. Nat Rev Mater. 2017;3.
Luzuriaga MA , Welch RP , Dharmarwardana M , Benjamin CE , Li S , Shahrivarkevishahi A , et al. Enhanced stability and controlled delivery of MOF-encapsulated vaccines and their immunogenic response in vivo. ACS Appl Mater Interfaces. 2019;11(10):9740–9746.
Samadian H , Maleki H , Allahyari Z , Jaymand M. Natural polymers-based light-induced hydrogels: Promising biomaterials for biomedical applications. Coord Chem Rev. 2020;420.
Jafari S , Izadi Z , Alaei L , Jaymand M , Samadian H , Kashani V , et al. Human plasma protein corona decreases the toxicity of pillar-layer metal organic framework. Sci Rep [Internet]. 2020;10(1):1–14. Available from: https://doi.org/10.1038/s41598-020-71170-z
An J , Geib SJ , Rosi NL . Cation-triggered drug release from a porous zinc-adeninate metal-organic framework. J Am Chem Soc. 2009;131(24):8376–8377.
Liu W , Yan Z , Zhang Z , Zhang Y , Cai G , Li Z. Bioactive and anti-corrosive bio-MOF-1 coating on magnesium alloy for bone repair application. J Alloys Compd. 2019;788:705–711.

Baati T , Njim L , Neffati F , Kerkeni A , Bouttemi M , Gref R , et al. In depth analysis of the in vivo toxicity of nanoparticles of porous iron(iii) metal–organic frameworks. Chem Sci. 2013;4(4):1597–1607.
Li R , Ren X , Zhao J , Feng X , Jiang X , Fan X , et al. Polyoxometallates trapped in a zeolitic imidazolate framework leading to high uptake and selectivity of bioactive molecules. J Mater Chem A. 2014;2(7):2168–2173.
Feng S , Zhang X , Shi D , Wang Z. Zeolitic imidazolate framework-8 (ZIF-8) for drug delivery: a critical review. Front Chem Sci Eng. 2021;15(2):221–237.
Roy S. Functionally graded coatings on biomaterials: a critical review. Mater Today Chem. [Internet]. 2020;18:100375. Available from: https://doi.org/10.1016/j.mtchem.2020.100375
Feng L , Wang KY , Willman J , Zhou HC . Hierarchy in metal-organic frameworks. ACS Cent Sci. 2020;6(3):359–367.
Kim K , Lee S , Jin E , Palanikumar L , Lee JH , Kim JC , et al. MOF × biopolymer: collaborative combination of metal-organic framework and biopolymer for advanced anticancer therapy. ACS Appl Mater Interfaces. 2019;11(31):27512–27520.
Abitha H , Kavitha V , Gomathi B , Ramachandran B. A recent investigation on shape memory alloys and polymers based materials on bio artificial implants-hip and knee joint. Mater Today Proc [Internet]. 2020;33:4458–4466. Available from: https://doi.org/10.1016/j.matpr.2020.07.711
Sabahi N , Chen W , Wang CH , Kruzic JJ , Li X. A review on additive manufacturing of shape-memory materials for biomedical applications. Jom [Internet]. 2020;72(3):1229–1253. Available from: https://doi.org/10.1007/s11837-020-04013-x
Green TR , Fisher J , Stone M , Wroblewski BM , Ingham E. Polyethylene particles of a “critical size” are necessary for the induction of cytokines by macrophages in vitro. Biomaterials. 1998;19(24):2297–2302.
Huang YF , Zhang ZC , Xu JZ , Xu L , Zhong GJ , He BX , et al. Simultaneously improving wear resistance and mechanical performance of ultrahigh molecular weight polyethylene via cross-linking and structural manipulation. Polymer (Guildf) [Internet]. 2016;90:222–231. Available from: http://dx.doi.org/10.1016/j.polymer.2016.03.011
Grupp TM , Holderied M , Mulliez MA , Streller R , Jäger M , Blömer W , et al. Biotribology of a vitamin E-stabilized polyethylene for hip arthroplasty – influence of artificial ageing and third-body particles on wear. Acta Biomater. 2014;10(7):3068–3078.
Pitenis AA , Urueña JM , McGhee EO , Hart SM , Reale ER , Kim J , et al. Challenges and opportunities in soft tribology. Tribol – Mater Surfaces Interfaces. 2017;11(4):180–186.
Huan W , Xing M , Cheng C , Li J. Facile fabrication of magnetic metal-organic framework nanofibers for specific capture of phosphorylated peptides. ACS Sustain Chem Eng. 2019;7(2):2245–2254.
Maglio M , Salamanna F , Brogini S , Borsari V , Pagani S , Nicoli Aldini N , et al. Histological, histomorphometrical, and biomechanical studies of bone-implanted medical devices: hard resin embedding. Biomed Res Int. 2020;2020:1804630.
Ravichandran R , Sundarrajan S , Venugopal JR , Mukherjee S , Ramakrishna S. Advances in polymeric systems for tissue engineering and biomedical applications. Macromol Biosci. 2012;12(3):286–311.
Cruz RLJ , Ross MT , Powell SK , Woodruff MA . Advancements in soft-tissue prosthetics part B: the chemistry of imitating life. Front Bioeng Biotechnol. 2020;8(April):1–23.
Green JJ , Elisseeff JH . Mimicking biological functionality with polymers for biomedical applications. Nature. 2016;540(7633):386–394.
Yunus M , Alsoufi MS . Experimental investigations into the mechanical, tribological, and corrosion properties of hybrid polymer matrix composites comprising ceramic reinforcement for biomedical applications. Int J Biomater. 2018;2018:9283291.
Chang BP , Akil HM , Nasir RM . Mechanical and tribological properties of zeolite-reinforced UHMWPE composite for implant application. Procedia Eng [Internet]. 2013;68:88–94. Available from: http://dx.doi.org/10.1016/j.proeng.2013.12.152
Schmidt BVKJ . Metal-organic frameworks in polymer science: polymerization catalysis, polymerization environment, and hybrid materials. Macromol Rapid Commun. 2020;41(1):1900333.
Kalaj M , Bentz KC , Ayala S , Palomba JM , Barcus KS , Katayama Y , et al. MOF-polymer hybrid materials: from simple composites to tailored architectures. Chem Rev. 2020;120(16):8267–8302.

Mahapatro A. Bio-functional nano-coatings on metallic biomaterials. Mater Sci Eng C. 2015;55:227–251.
Hornberger H , Virtanen S , Boccaccini AR . Biomedical coatings on magnesium alloys – a review. Acta Biomater [Internet]. 2012;8(7):2442–2455. Available from: http://dx.doi.org/10.1016/j.actbio.2012.04.012
El Hankari S , Bousmina M , El Kadib A. Biopolymer@metal-organic framework hybrid materials: a critical survey. Prog Mater Sci [Internet]. 2019;106(November):100579. Available from: https://doi.org/10.1016/j.pmatsci.2019.100579
Anand A , Irfan Ul Haq M , Vohra K , Raina A , Wani MF . Role of green tribology in sustainability of mechanical systems: a state of the art survey. Mater Today Proc [Internet]. 2017;4(2):3659–3665. Available from: http://dx.doi.org/10.1016/j.matpr.2017.02.259
Amann T , Dold C , Kailer A. Complex fluids in tribology to reduce friction: mesogenic fluids, ionic liquids and ionic liquid crystals. Tribol Int. 2013;65:3–12.
Chen W , Amann T , Kailer A , Rühe J. Thin-film lubrication in the water/octyl β-d-glucopyranoside system: macroscopic and nanoscopic tribological behavior. Langmuir. 2019;35(22):7136–7145.
Chen W , Amann T , Kailer A , Rühe J. Macroscopic friction studies of alkylglucopyranosides as additives for water-based lubricants. Lubricants. 2020;8(1):11.
Ghaednia H , Hossain MS , Jackson RL . Tribological performance of silver nanoparticle–enhanced polyethylene glycol lubricants. Tribol Trans. 2016;59(4):585–592.
Torres O , Andablo-Reyes E , Murray BS , Sarkar A. Emulsion microgel particles as high-performance bio-lubricants. ACS Appl Mater Interfaces. 2018;10(32):26893–26905.
Bayer IS . Advances in tribology of lubricin and lubricin-like synthetic polymer nanostructures. Lubricants. 2018;6(2):30.
Zhang HY , Zhou M. The influence of protein concentration on the biotribological properties of the stem-cement interface. Biomed Mater Eng. 2014;24(1):173–179.
Aris AZ , Mohd Hir ZA , Razak MR . Metal-organic frameworks (MOFs) for the adsorptive removal of selected endocrine disrupting compounds (EDCs) from aqueous solution: a review. Appl Mater Today [Internet]. 2020;21:100796. Available from: https://doi.org/10.1016/j.apmt.2020.100796
Gao D-Y , Liu Z , Cheng Z-L. 2D Ni-Fe MOF nanosheets reinforced poly(vinyl alcohol) hydrogels with enhanced mechanical and tribological performance. Colloids Surfaces A Physicochem Eng Asp [Internet]. 2021;610(October 2020):125934. Available from: https://doi.org/10.1016/j.colsurfa.2020.125934
Zhang G , Xie G , Si L , Wen S , Guo D. Ultralow friction self-lubricating nanocomposites with mesoporous metal-organic frameworks as smart nanocontainers for lubricants. ACS Appl Mater Interfaces. 2017;9(43):38146–38152.

The Use of C.P. Titanium in Medical Friction Pairs

Miletic, K. G. , Taylor, T. N. , Martin, E. T. , Vaidya, R. , and Kaye, K. S. 2014. Readmissions after diagnosis of surgical site infection following knee and hip arthroplasty. Infect Control Hosp Epidemiol 35:152–157.
Sheykin, S. E. , Pohrelyuk, I. M. , and Mamalis, A. G. 2014. On the effectiveness of commercially pure titanium-UHMWPE endoprosthetic friction pairs. J Biol Phys Chem 14:11–17.
Pinchuk, L. C. , Nikolaev, V. I. , Tsvetkova, E. A. , and Goldade, V. A. 2006. Tribology and biophysics of artificial joints. Oxford: Elsevier.
Filippenko, V. A. , and Tankut, A. V. 2009. Evolution of joint prosthetics problem. Int Med J 1:70–74.
Charnley, J. 1961. Arthroplasty of the hip. A new operation. Lancet 1:1129–1132.
Nadeev, A. , and Ivannikov, S.V. 2015. Endoprostheses of the hip joint in Russia: the construction philosophy, implant review, rational choice. Knowledge Lab.
Kurtz, S. M. 2009. Ultra high molecular weight polyethylene in total joint replacement and medical devices. Burlington: Academic Press.
Sidambe, A. T. 2014. Biocompatibility of advanced manufactured titanium implants–a review. Mater 7:8168–8188.

Rahman, M. , Reid, I. , Duggan, P. , Dowling, D. P. , Hughes, G. , and Hashmi, M. S. J. 2007. Structural and tribological properties of the plasma nitrided Ti-alloy biomaterials: Influence of the treatment temperature. Surf Coat Tech 201:4865–4872.

Manhabosco, T. M. , Tamborim, S. M. , dos Santos, C. B. , and Muller, I. L. 2011. Tribological, electrochemical and tribo-electrochemical characterization of bare and nitrided Ti6Al4V in simulated body fluid solution. Corros Sci 53:1786–1793.

Kapzhinski, M. P. , Kinast, E. J. , and dos Santos, C. A. 2003. Near-surface composition and tribological behaviour of plasma nitrided titanium. J Phys Appl Phys 36:1858–1863.

Nolan, D. , Huang, S. W. , Leskovsek, V. , and Braun, S. 2006. Sliding wear of titanium nitride thin films deposited on Ti-6Al-4V alloy by PVD and plasma nitriding processes. Surf Coat Tech 200:5698–5705.

Pohrelyuk, I. M. , Sheykin, S. E. , Dub, S. M. et al. 2016. Increasing of functionality of c.p. titanium/UHMWPE tribo-pairs by thermodiffusion nitriding of titanium component. Biotribology 7:38–45.

Sheykin, S. Ye. , Pohreliuk, I.M. , Iefrosinin, D.V. , Rostotskiy I. Yu. , and Sergach, D.A. 2015. The use of titanium in the friction units of artificial joints. Sci Innov 11:5–10.

Pohrelyuk, I. , and Fedirko, V. 2012. Chemico-thermal treatment of titanium alloys – nitriding. In Titanium alloys – towards achieving enhanced properties for diversified applications, ed. A. K. M. Nurul Amin , 141–174. Rijeka: InTech.

Novikov, N. V. , Rosenberg, O. A. , and Gavlik, J. 2011. Endoprostheses of the human joints: Materials and technologies. Kyiv: ISM them. VN Bakul NAS of Ukraine.

Paschenko, Ye. A. , Sheykin, S. Ye. , and Iefrosinin, D. V. 2013. Tools for precision diamond machining of spherical heads of endoprostheses from pure titanium. J Superhard Mater 35:175–182.

Grushko, A. V. , Sheykin, S. E. , and Rostotskiy, I. Y. 2012. Contact pressure in hip endoprosthetic swivel joints. J Frict Wear 33:124–129.

Pohrelyuk, I. M. , Sheikin, S. Ye. , and Efrosinin, D. V. 2014. Surface hardening of VT1-0 titanium in the course of thermodiffusion saturation with nitrogen within the temperature range 650–750oC. Mater Sci 50:70–79.

Hultman, L. , Sundgren, J.-E. , Greene, J. E. , Bergstrom, D. B. , and Petrov, I. 1995. High-flux low-energy (~20 eV) N+2 ion irradiation during TiN deposition by reactive magnetron sputtering: Effects on microstructure and preferred orientation. J Appl Phys 12:5395–5404.

http://obuch.com.ua/informatika/11247/index.html.

Ermakov, F. 2008. Tribological physics of liquid crystals. Gomel: IMMS of the National Academy of Sciences of Belarus.

Sheykin, S. , Pohrelyuk, I. , Rostotskyi, I. , Iefrosinin, D. , Tuszynski, W. , Mankowska-Snopczynska, A. 2018. Tribological behavior of the friction pair “GRADE 2/PE-UHMW” and the technology of the production of its spherical part made of GRADE 2. Tribologia 6:137–148.

Chernyakova, Yu. M. , and Pinchuk, L. S. 2007. Synovial joint as a clever friction unit. Frict Wear 28:410–417.

Ermakov, S. F. , and Beletsky, A. V. 2011. Tribological principles of blood serum preparations as a liquid crystalline medium for therapeutic correction of synovial joints. Frict Wear 32:65–71.

Ermakov, S. F. , Beletskii, A. V. , and Nikolaev, V. I. 2011. Tribological principles of developing medicinal preparations based on blood serum as a liquid crystalline medium for therapeutic correction of synovial joints. J Frict Wear 32:49–53.

Novikov, N. V. , Rozenberg, O. A. , and Gavlik, Y. 2011. Endoprosthesis of human joints: materials and technologies (in Russian). V. Kyiv: Bakul Institute for Superhard Materials of the NAS of Ukraine.

Oonishi, H. 2000. Clinical experience with ceramics in total hip replacement. Clin Orthop 379:77–84.

Santos, E. M. , Vohra, S. , Catledge, S. A. , McClenny, M. D. , Lemons, J. , Moore, K. D. 2004. Examination of surface and material properties of explanted zirconia femoral heads, J Arthroplasty 19:30–34.

Electrochemical Techniques Applied to the Tribocorrosion Tests

American Society for Testing and Materials. ASTM G 119-09. Standard Guide for Determining Synergism between Wear and Corrosion. ASTM International West Conshohocken, PA: 2009.

American Society for Testing and Materials. ASTM G 40-17. Standard terminology relating to wear and erosion. ASTM International West Conshohocken, PA: 2017.

López-Ortega A , Arana JL , Bayón R. Tribocorrosion of passive materials: a review on test procedures and standards. International Journal of Corrosion. 2018; 18: 7345346.

Berradja A , Déforge D , Nogueira RP , Ponthiaux P , Wenger F , Celis JP . An electrochemical noise study of tribocorrosion processes of AISI 304 L in Cl− and media. Journal of Physics D: Applied Physics. 2006; 39 (15): 3184.

Mathew MT , Uth T , Hallab NJ , Pourzal R , Fischer A , Wimmer MA . Construction of a tribocorrosion test apparatus for the hip joint: validation, test methodology and analysis. Wear. 2011; 271 (9–10): 2651–2659.

Landolt D , Mischler S , Stemp M , Barril S. Third body effects and material fluxes in tribocorrosion systems involving a sliding contact. Wear. 2004; 256 (5): 517–524.

Jiang J , Stack MM , Neville A. Modelling the tribo-corrosion interaction in aqueous sliding conditions. Tribology International. 2002; 35 (10): 669–679.

Ferreira DF , Almeida SMA , Soares RB , Juliani L , Bracarense AQ , Lins VDFC , Junqueira RMR . Synergism between mechanical wear and corrosion on tribocorrosion of a titanium alloy in a Ringer solution. Journal of Materials Research and Technology. 2019; 8 (2): 1593–1600.

Rasool G , Y. El Shafei and M.M. Stack . Mapping tribo-corrosion behaviour of TI-6AL-4V Eli in laboratory simulated hip joint environments. Lubricants. 2020; 8 (7): 69.

Sampaio M , Buciumeanu M. , Henriques B , Silva FS , Souza JCM , Gomes JR . Comparison between PEEK and Ti6Al4V concerning micro-scale abrasion wear on dental applications. Journal of the Mechanical Behavior of Biomedical Materials. 2016; 60: 212–219.

Holmes D , Sharifi S , Stack MM . Tribo-corrosion of steel in artificial saliva. Tribology International. 2014; 75: 80–86.

American Society for Testing and Materials. ASTM G133-05. Standard Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear. ASTM International West Conshohocken, PA: 2005a.

American Society for Testing and Materials. ASTM G 99-05. Standard test method for wear testing with a pin-on-disk apparatus. ASTM International West Conshohocken, PA: 2005b.

Abolusoro OP , Akinlabi ET . Tribocorrosion Measurements and Behaviour in Aluminium Alloys: An Overview. Journal of Bio- and Tribo-Corrosion. 2020; 6 (4): 1–13.

Barros CDR , Rocha JC , Bastos IN , Ponciano Gomes JAC . Tribocorrosion of Ti6Al4V and NiCr Implant Alloys: Effect of Galvanic Interaction. Journal of Bio- and Tribo-Corrosion. 2020a; 6: 117.

Dalbert V , Mary N , Normand B , Verdu C , Saedlou S. In situ determinations of the wear surfaces, volumes and kinetics of repassivation: Contribution in the understanding of the tribocorrosion behaviour of a ferritic stainless steel in various pH. Tribology International. 2010; 150: 106374.

López-Ortega A , Arana JL , Bayón R. On the comparison of the tribocorrosion behavior of passive and non-passivating materials and assessment of the influence of agitation. Wear. 2020; 456: 203388.

Voutat C , Nohava J , Wandel J , Zysset P. The dynamic friction coefficient of the wet bone-implant interface: influence of load, speed, material and surface finish. Biotribology. 2019; 17: 64–74.

Sivakumar B , Pathak LC , Singh R. Role of surface roughness on corrosion and fretting corrosion behaviour of commercially pure titanium in Ringer’s solution for bio-implant application. Applied Surface Science. 2017; 401: 385–398.

Silva DP , Churiaque C , Bastos IN , Sánchez-Amaya JM . Tribocorrosion study of ordinary and laser-melted Ti6Al4V alloy. Metals. 2016; 6 (10): 253.

Kappel MAA , Silva DP , Sánchez-Amaya JM , Domingos RP , Bastos IN . Análise não Estacionária Aplicada a Sinais de Tribocorrosão. Revista Virtual de Química 2015; 7 (5): 1651–1662.

Li DG , Wang JD , Chen DR , Liang P. Influence of molybdenum on tribo-corrosion behavior of 316L stainless steel in artificial saliva. Journal of Bio-and Tribo-Corrosion. 2015;1(2): 14.
Souza JCM , Tajiri HA , Morsch CS , Buciumeanu M , Mathew MT , Silva FS , Henriques B. Tribocorrosion behavior of Ti6Al4V coated with a bio-absorbable polymer for biomedical applications. Journal of Bio-and Tribo-Corrosion. 2015; 1 (4): 27.
Wimmer MA , Laurent MP , Mathew MT , Nagelli C , Liao Y , Marks LD , Jacobs DD , Fischer A. The effect of contact load on CoCrMo wear and the formation and retention of tribofilms. Wear. 2015; 332: 643–649.
Mathew MT , Abbey S , Hallab NJ , Hall DJ , Sukotjo C , Wimmer MA . Influence of pH on the tribocorrosion behavior of CpTi in the oral environment: synergistic interactions of wear and corrosion. Journal of Biomedical Materials Research Part B: Applied Biomaterials. 2012; 100 (6): 1662–1671.
Kumar S , Narayanan TS , Raman SGS , Seshadri SK . Evaluation of fretting corrosion behaviour of CP-Ti for orthopaedic implant applications. Tribology International. 2010; 43 (7): 1245–1252.
Yan Y , Neville A , Dowson D , Williams S , Fisher J. Tribo-corrosion analysis of wear and metal ion release interactions from metal-on-metal and ceramic-on-metal contacts for the application in artificial hip prostheses. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology. 2008; 222 (3): 483–492.
Vieira AC , Ribeiro AR , Rocha LA , Celis JP . Influence of pH and corrosion inhibitors on the tribocorrosion of titanium in artificial saliva. Wear. 2006; 261 (9): 994–1001.
Déforge D , Huet F , Nogueira RP , Ponthiaux P , Wenger F. Electrochemical noise analysis of tribocorrosion processes under steady-state friction regime. Corrosion. 2006; 62 (6): 514–521.
Espallargas N , Johnsen R , Torres C , Muñoz AI . A new experimental technique for quantifying the galvanic coupling effects on stainless steel during tribocorrosion under equilibrium conditions. Wear. 2013; 307 (1–2): 190–197.
Radice S , Holcomb T , Pourzal R , Hallab NJ , Laurent MP , Wimmer MA . Investigation of CoCrMo material loss in a novel bio-tribometer designed to study direct cell reaction to wear and corrosion products. Biotribology. 2019; 18: 100090.
Puppulin L , Leto A , Wenliang Z , Sugano N. and Pezzotti G. Innovative tribometer for in situ spectroscopic analyses of wear mechanisms and phase transformation in ceramic femoral heads. Journal of the Mechanical Behavior of Biomedical Materials. 2014; 31: 45–54.
Bruschi S , Bertolini R , Medeossi F , Ghiotti A , Savio E , Shivpuri R. Case study: The application of machining-conditioning to improve the wear resistance of Ti6Al4V surfaces for human hip implants. Wear. 2018; 394: 134–142.
Yan Y , Neville A , Hesketh J , Dowson D. Real-time corrosion measurements to assess biotribocorrosion mechanisms with a hip simulator. Tribology International. 2013; 63: 115–122.
Hua Z , Dou P , Jia H , Tang F , Wang X , Xiong X , Gao L , Huang X , Jin Z. Wear test apparatus for friction and wear evaluation hip prostheses. Frontiers in Mechanical Engineering. 2019; 5: 12.
Yan Y , Neville A , Dowson D , Williams S , Fisher J. The influence of swing phase load on the electrochemical response, friction, and ion release of metal-on-metal hip prostheses in a friction simulator. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology. 2009; 223 (3): 303–309.
Corne P , De March P , Cleymand F , Geringer J. Fretting-corrosion behavior on dental implant connection in human saliva. Journal of the Mechanical Behavior of Biomedical Materials. 2019; 94: 86–92.
Dalmau Borrás A , Buch AR , Cardete AR , Navarro-Laboulais J , Munoz AI . Chemo-mechanical effects on the tribocorrosion behavior of titanium/ceramic dental implant pairs in artificial saliva. Wear. 2019; 426: 162–170.
Simsek I , Ozyurek D. Investigation of the wear and corrosion behaviors of Ti5Al2. 5Fe and Ti6Al4V alloys produced by mechanical alloying method in simulated body fluid environment. Materials Science and Engineering: C. 2019; 94: 357–363.
Pejaković V , Totolin V , Ripoll MR . Tribocorrosion behaviour of Ti6Al4V in artificial seawater at low contact pressures. Tribology International. 2018; 119: 55–65.
Alves SA , Bayón R , de Viteri VS , Garcia MP , Igartua A , Fernandes MH , Rocha LA . Tribocorrosion behavior of calcium-and phosphorous-enriched titanium oxide films and study of osteoblast interactions for dental implants. Journal of Bio- and Tribo-Corrosion. 2015; 1 (3): 23.

Licausi MP , Muñoz AI , Borrás VA , Espallargas N. Tribocorrosion mechanisms of Ti6Al4V in artificial saliva by zero-resistance ammetry (ZRA) technique. Journal of Bio-and Tribo-Corrosion. 2015; 1 (1): 8.

Swaminathan V , Gilbert JL . Potential and frequency effects on fretting corrosion of Ti6Al4V and CoCrMo surfaces. Journal of Biomedical Materials Research Part A. 2013; 101 (9): 2602–2612.

Dimah MK , Albeza FD , Borrás VA , Muñoz IA . Study of the biotribocorrosion behaviour of titanium biomedical alloys in simulated body fluids by electrochemical techniques. Wear. 2012; 294: 409–418.

Tekin KC , Malayoglu U. Assessing the tribocorrosion performance of three different nickel-based superalloys. Tribology Letters. 2010; 37 (3): 563–572.

International Organization for Standardization. ISO 4287:1997(en). Geometrical Product Specifications (GPS) — Surface texture: Profile method — Terms, definitions and surface texture parameters. ISO;1997.

International Organization for Standardization. ISO 25178-2 :2012(en).Geometrical product specifications (GPS) — surface texture: areal — part 2: terms, definitions and surface texture parameters. ISO; 2012.

Alves SA , Rossi AL , Ribeiro AR , Toptan F , Pinto AM , Shokuhfar T , Cellis JP , Rocha LA . Improved tribocorrosion performance of bio-functionalized TiO2 nanotubes under two-cycle sliding actions in artificial saliva. Journal of the Mechanical Behavior of Biomedical Materials. 2018; 80: 143–154.

Liamas E , Thomas OR , Muñoz AI , Zhang ZJ . Tribocorrosion behaviour of pure titanium in bovine serum albumin solution: A multiscale study. Journal of the Mechanical Behavior of Biomedical Materials. 2020; 102: 103511.

Zhao GH , Aune RE , Espallargas N. Tribocorrosion studies of metallic biomaterials: The effect of plasma nitriding and DLC surface modifications. Journal of the Mechanical Behavior of Biomedical Materials. 2016; 63: 100–114.

Butt A , Lucchiari NB , Royhman D , Runa MJ , Mathew MT , Sukotjo C , Takoudis CG . Design, development, and testing of a compact tribocorrosion apparatus for biomedical applications. Journal of Bio- and Tribo-Corrosion. 2015; 1: 4.

Stack MM , Corlett N , Zhou S. A methodology for the construction of the erosion-corrosion map in aqueous environments. Wear. 1997; 203: 474–488.

Stack MM . Mapping tribo-corrosion processes in dry and in aqueous conditions: some new directions for the new millennium. Tribology International. 2002; 35 (10): 681–689.

Diomidis N , Celis JP , Ponthiaux P , Wenger F. A methodology for the assessment of the tribocorrosion of passivating metallic materials. Lubrication Science. 2009; 21 (2): 53–67.

Barros CDR , Rocha JC , Braz BF , Santelli RE , Gomes JACP . Galvanic Corrosion of Ti6Al4V Coupled with NiCr as a Dental Implant Alloy in Fluoride Solutions. International Journal of Electrochemical Science. 2020b; 15: 394–411.

European Standards. UNE 112086: 2016. Tribocorrosion testing procedure for passivating materials. UNE (Normalización Española); 2016.

Silva RCC , Nogueira RO , Bastos IN . Tribocorrosion of UNS S32750 in chloride medium: Effect of the load level. Electrochimica Acta. 2011; 56 (24): 8839–8845.

Sun D , Wharton JA , Wood RJK . Effects of proteins and pH on tribocorrosion performance of cast CoCrMo—a combined electrochemical and tribological study. Tribology-Materials, Surfaces & Interfaces. 2008; 2 (3): 150–160.

Geringer J , Forest B , Combrade P. Fretting-corrosion of materials used as orthopaedic implants. Wear. 2005; 259 (7–12): 943–951.

Jemmely P , Mischler S , Landolt D. Electrochemical modeling of passivation phenomena in tribocorrosion. Wear. 2000; 237 (1): 63–76.

Licausi MP , Muñoz AI , Borrás VA . Influence of the fabrication process and fluoride content on the tribocorrosion behaviour of Ti6Al4V biomedical alloy in artificial saliva. Journal of the Mechanical Behavior of Biomedical Materials. 2013; 20: 137–148.

Future Outlooks in Biotribology

Alessandro Ruggiero , Alessandro Sicilia . Lubrication modeling and wear calculation in artificial hip joint during the gait, Tribol. Int., 2020, Vol. 142, p. 105993.

C Xie . Bio-inspired nanofunctionalisation of biomaterial surfaces: A review, Biosurf. Biotribol., 2019, Vol. 5, Iss. 3, pp. 83–92.

Shiju Vadakkumpurath , Abhijith Njarakkadu Venugopal , Sudeep Ullattil . Influence of micro-textures on antibacterial behaviour of titanium-based implant surfaces: In vitro studies, Biosurf. Biotribol., 2019, Vol. 5, Iss. 1, pp. 20–23.

Liming Shu , Shihao Li , Naohiko Sugita . Systematic review of computational modelling for biomechanics analysis of total knee replacement, Biosurf. Biotribol., Vol. 6, Iss. 1, 2020, pp. 3–11.